

# Experimental particle. physics

**esipap**...  
European School of Instrumentation  
in Particle & Astroparticle Physics

**6.**

experiments to detect  
“invisible” particles

# A bit of neutrino history...

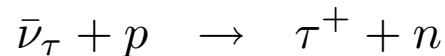
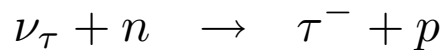
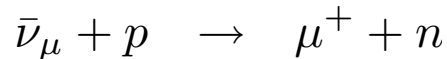
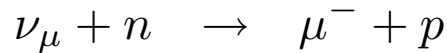
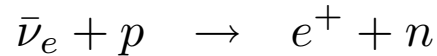
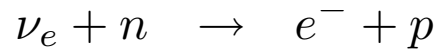
- **1930 Neutrino postulated**
- 1934 Neutrino name and interaction theory
- 1938 Solar neutrino flux calculation
- 1946 Idea of neutrino chlorine detector
- **1956 Neutrino observation**
- 1957 Idea of neutrino oscillation
- 1958 Neutrino are Left-Handed
- 1962 There are (at least) 2 neutrino species:  $n_{\mu}$ ,  $n_e$
- **1968 Solar neutrino deficit**
- 1973 Neutral Current neutrino interactions observed
- 1975 Tau lepton and the third neutrino
- 1986 Solar deficit again: maybe atmospheric?
- **1987 Neutrino from SNI987A**
- 1989 There are only 3 light neutrino families
- 1991 Still solar deficit
- **1998 Atmospheric neutrino oscillation**
- **2002 Solar neutrino oscillation confirmed**
- 2004 Atmospheric oscillation confirmed at accelerator
- **Pauli**
- *Fermi*
- *Bethe*
- *Pontecorvo*
- **Reines & Cowan**
- *Pontecorvo*
- *Goldhaber*
- *Lederman, Schwartz & Steinberger*
- **Davis**
- *Gargamelle*
- *Perl*
- *Kamiokande*
- **Kamiokande, IMB**
- *LEP Collaborations*
- *Gallex, SAGE*
- **Super-Kamiokande**
- **SNO, KamLand**
- *K2K*

# Neutrino interactions

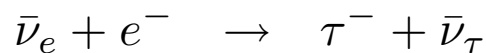
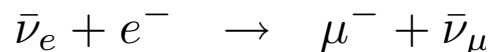
Neutron detection only via weak interaction ...

Possible reactions:

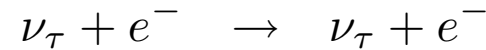
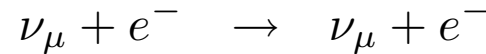
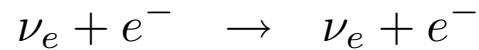
Charged Current Reactions:



...

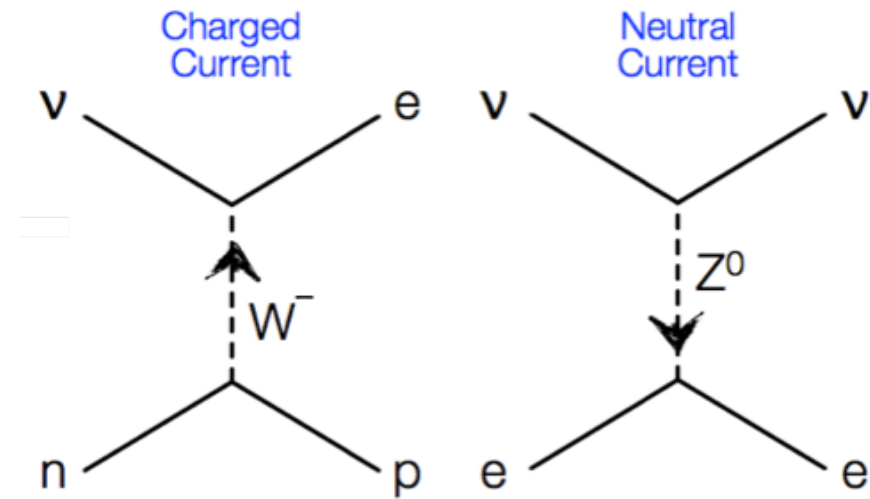


Neutral Current Reactions:



Remark:

Neutral Current  $\nu N$ -interactions not usable due to small energy transfer



Neutrino nucleon x-Section:

[examples]

10 GeV neutrinos:  $\sigma = 7 \cdot 10^{-38} \text{ cm}^2/\text{nucleon}$

Interaction probability for 10 m Fe-target:  $R = \sigma \cdot N_A [\text{mol}^{-1}/\text{g}] \cdot d \cdot \rho = 3.2 \cdot 10^{-10}$   
with  $N_A = 6.023 \cdot 10^{23} \text{ g}^{-1}$ ;  $d = 10 \text{ m}$ ;  $\rho = 7.6 \text{ g/cm}^3$

Solar neutrinos [100 keV]:  $\sigma = 7 \cdot 10^{-45} \text{ cm}^2/\text{nucleon}$

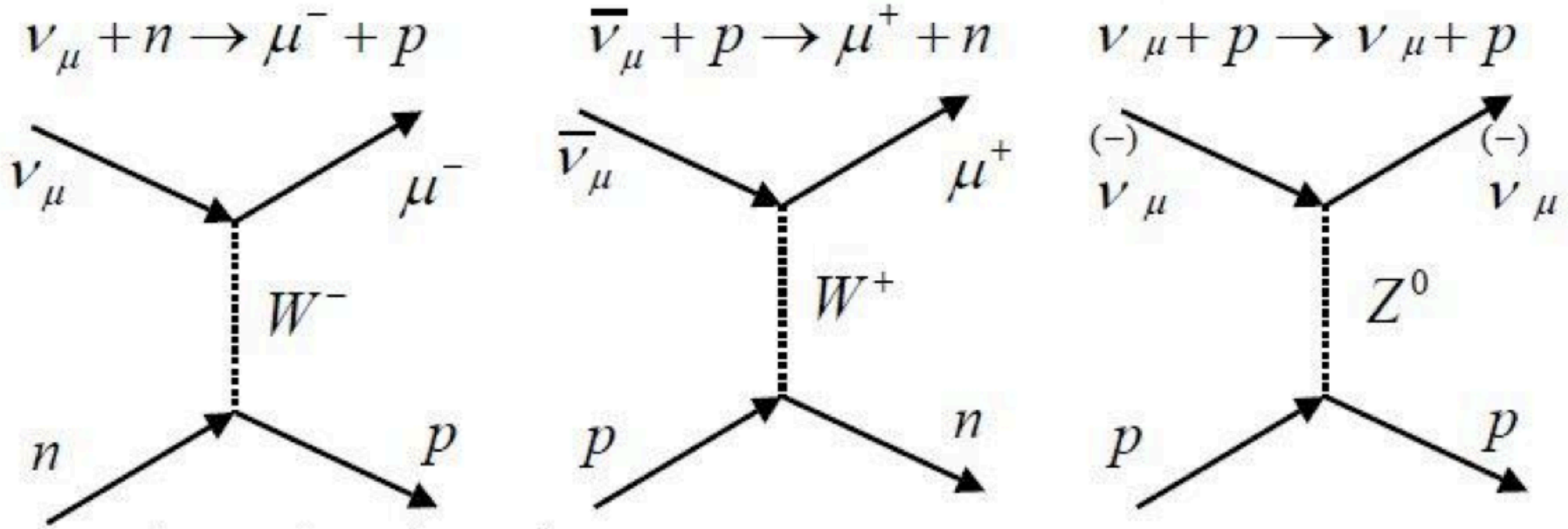
Interaction probability for earth:  $R = \sigma \cdot N_A [\text{mol}^{-1}/\text{g}] \cdot d \cdot \rho \approx 4 \cdot 10^{-14}$   
with  $N_A = 6.023 \cdot 10^{23} \text{ g}^{-1}$ ;  $d = 12000 \text{ km}$ ;  $\rho = 5.5 \text{ g/cm}^3$

# Neutrino interactions: V-e

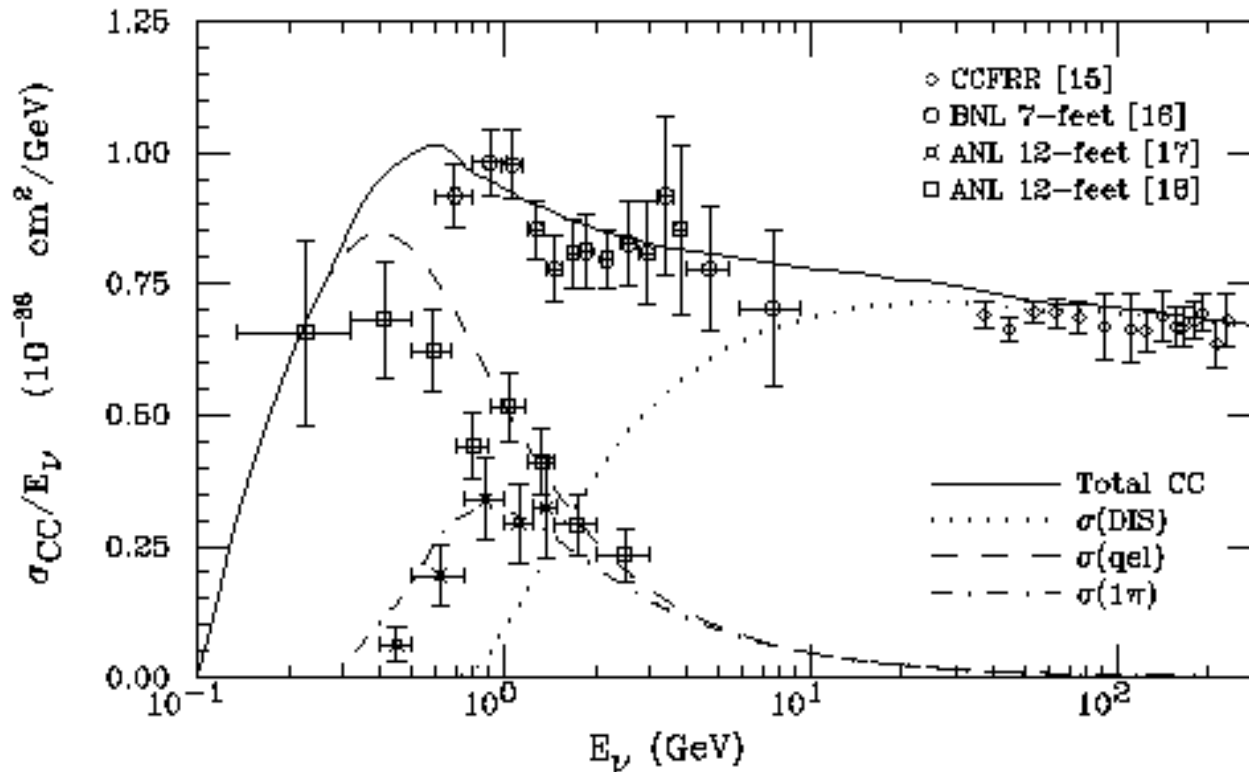
Process	Total Cross section
$\nu_{\mu} + e^{-} \rightarrow \mu^{-} + \nu_e$	$\frac{G_F^2 s}{\pi} \quad 1.7 \cdot 10^{-43} \left( \frac{E}{10\text{MeV}} \right) \text{cm}^2$
$\nu_e + e^{-} \rightarrow \nu_e + e^{-}$	$\frac{G_F^2 s}{4\pi} \left[ (2 \sin^2 \theta_W - 1)^2 + \frac{4}{3} \sin^4 \theta_W \right]$
$\bar{\nu}_e + e^{-} \rightarrow \bar{\nu}_e + e^{-}$	$\frac{G_F^2 s}{4\pi} \left[ \frac{1}{3} (2 \sin^2 \theta_W + 1)^2 + 4 \sin^4 \theta_W \right]$
$\nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-}$	$\frac{G_F^2 s}{4\pi} \left[ (2 \sin^2 \theta_W - 1)^2 + \frac{4}{3} \sin^4 \theta_W \right]$
$\bar{\nu}_{\mu} + e^{-} \rightarrow \bar{\nu}_{\mu} + e^{-}$	$\frac{G_F^2 s}{4\pi} \left[ \frac{1}{3} (2 \sin^2 \theta_W - 1)^2 + 4 \sin^4 \theta_W \right]$

# Neutrino interactions: $\nu$ -nucleon

- Interaction happens with whole nucleon
  - ✓ Nucleon can at best undergo an *isospin* transition in case of charged current (quasi-elastic scattering)
  - ✓ In case of neutral current, scattering is perfectly elastic



# Neutrino interactions: quasi-elastic $\nu$ -nucleon



Threshold is different for different neutrino flavors...

Paolo Lipari, Maurizio Lusignoli, Francesca Sartogo, "The neutrino cross section and upward going muons" <http://arxiv.org/abs/hep-ph/9411341>

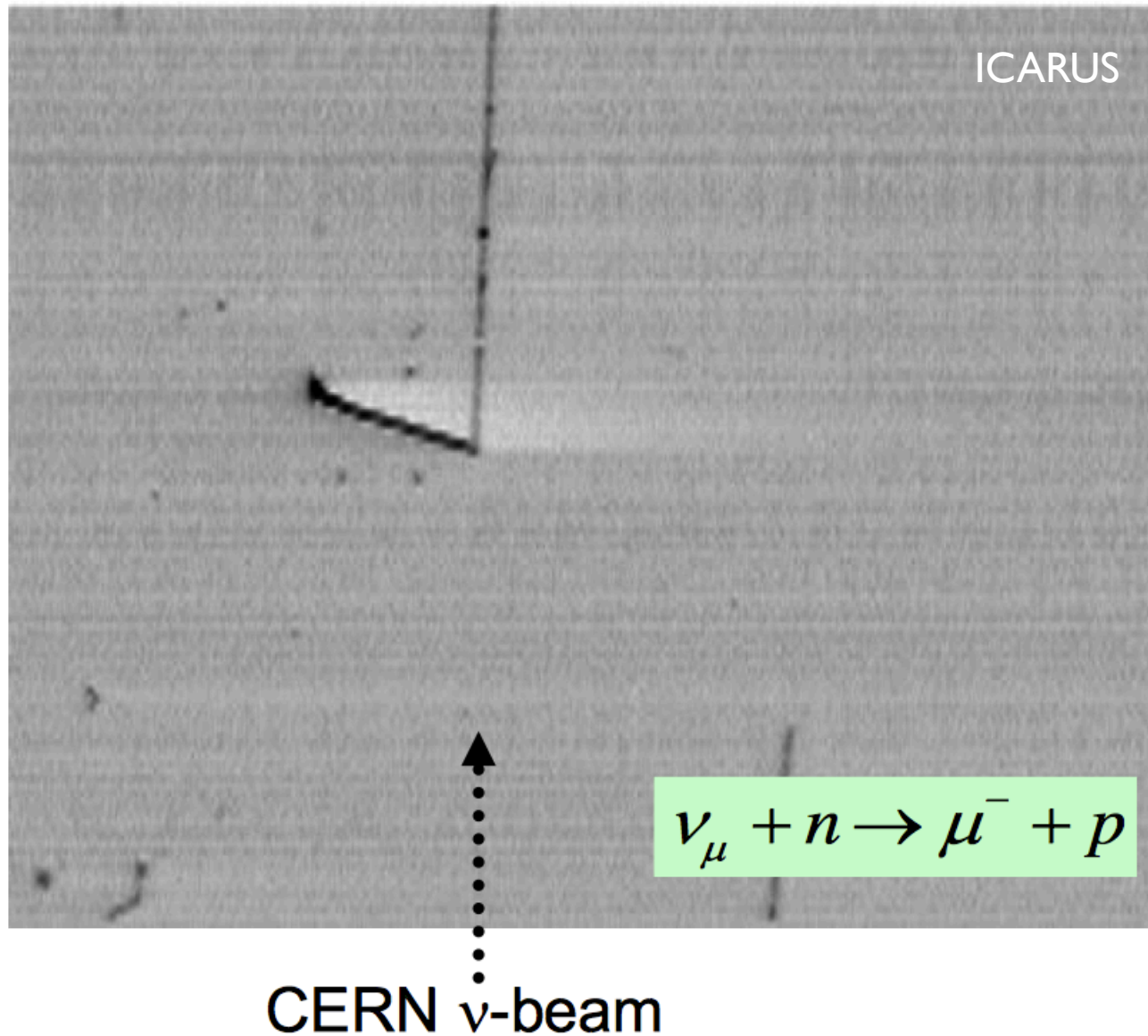
$$E \ll m_n \quad \sigma(\nu n) = \sigma(\bar{\nu} p) \approx$$

$$9.75 \cdot 10^{-42} \left( \frac{E}{10 \text{ MeV}} \right)^2 \text{ cm}^2$$

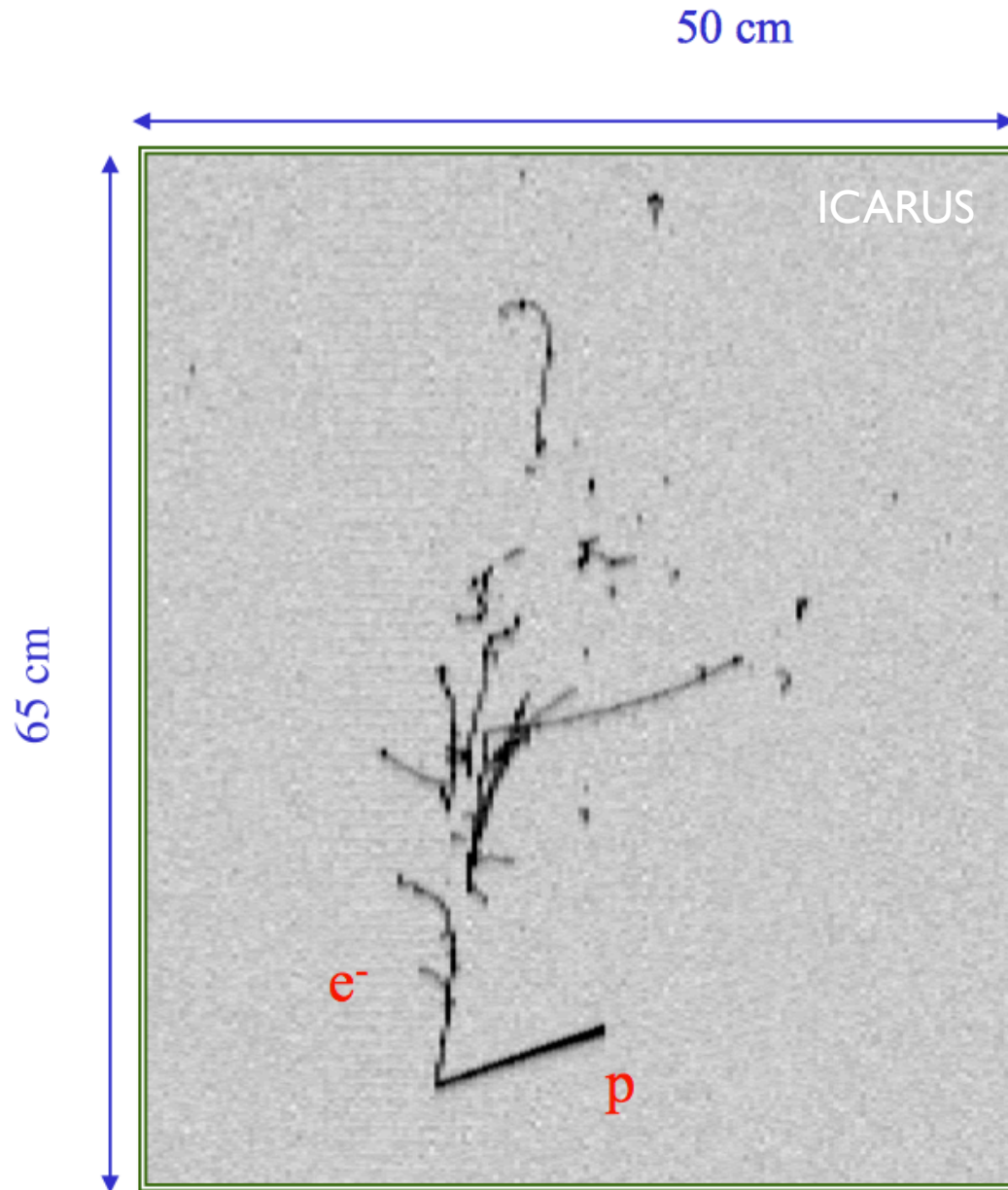
$$E > 1 \text{ GeV}$$

$$\sigma/E \sim \text{constant}$$

# A neutrino interaction...

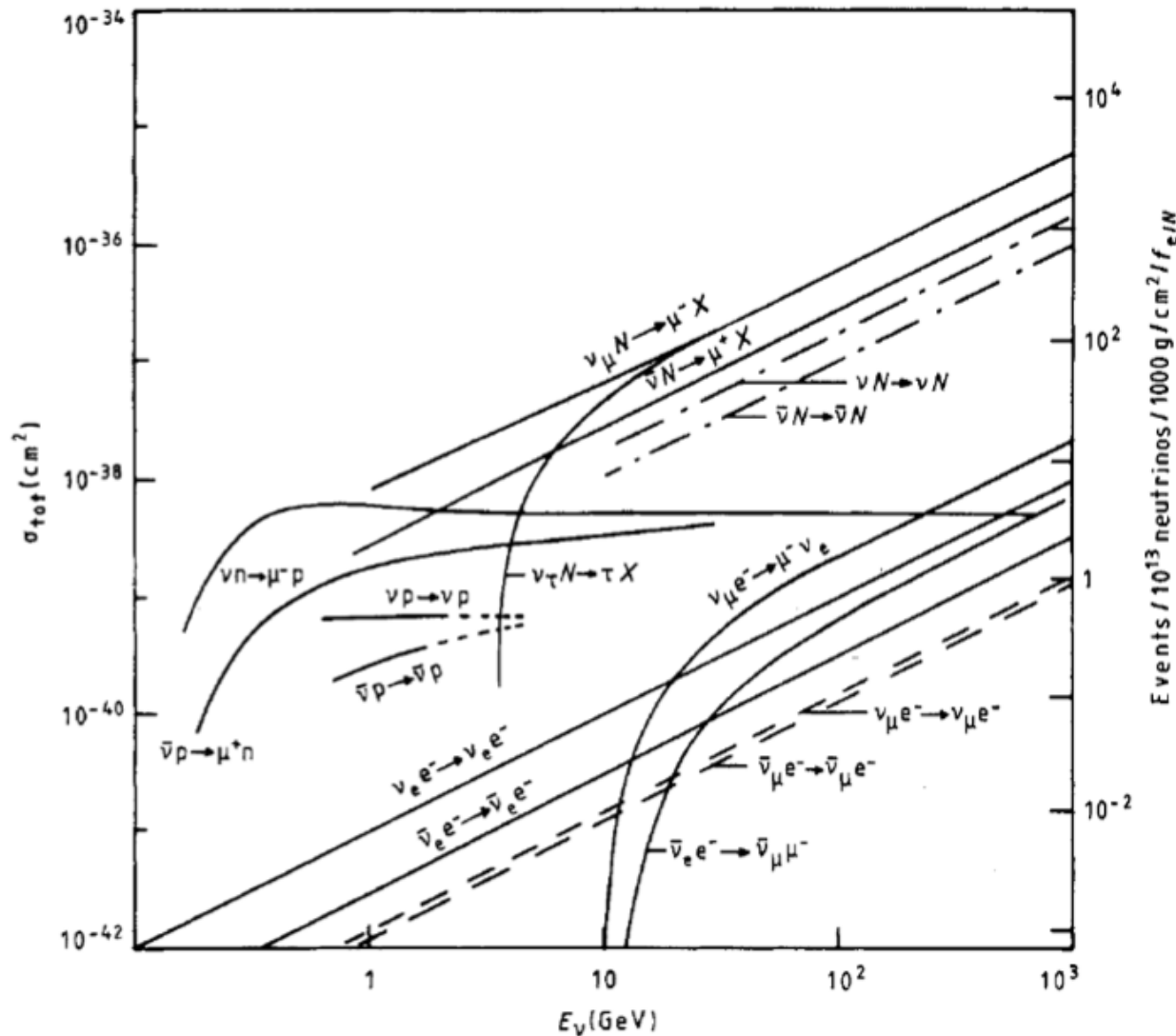


# Another neutrino interaction...





# Neutrino interaction cross sections comparison



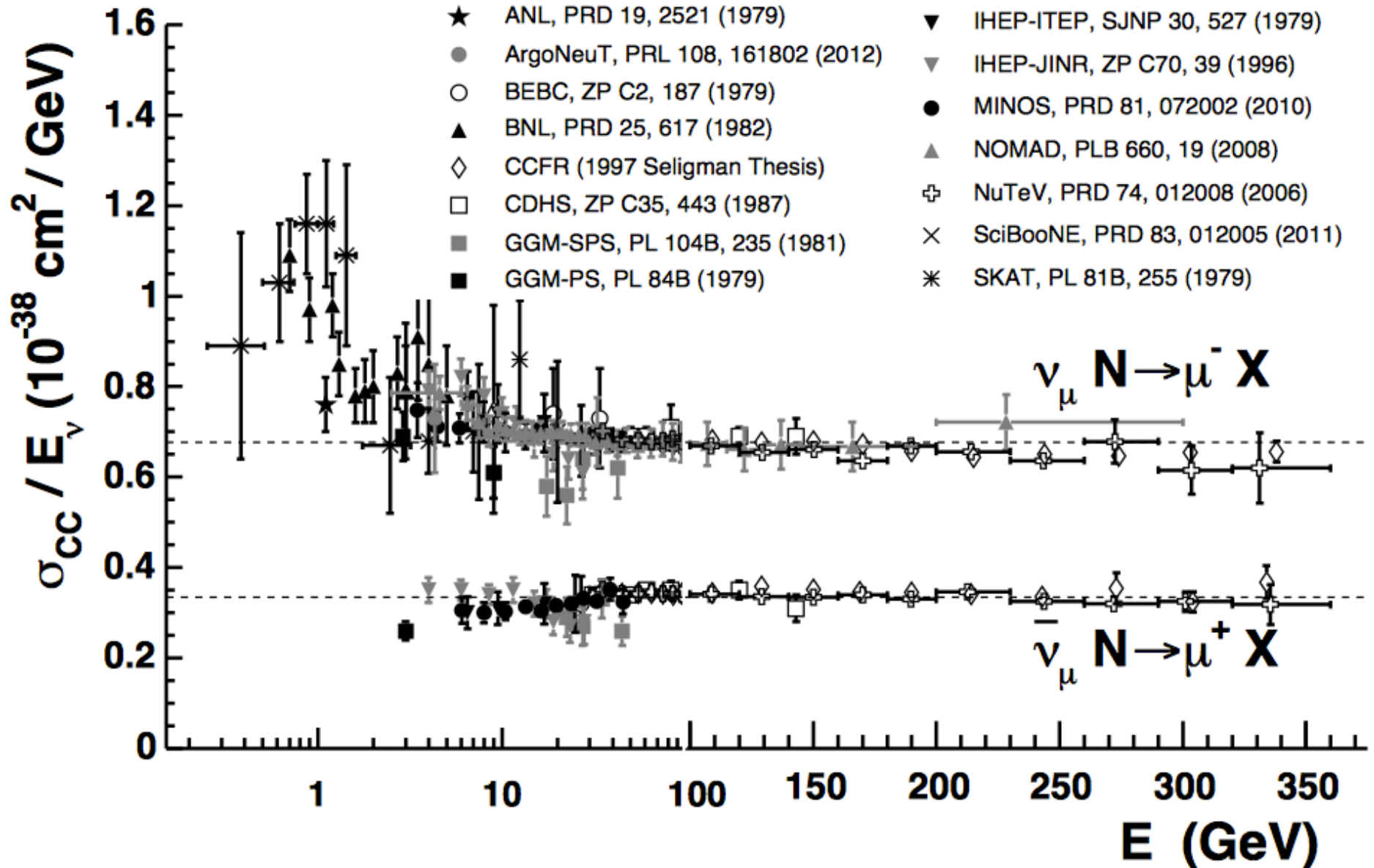
close to thresholds...

$$\sigma \sim \frac{(s - m_\mu^2)^2}{s}$$

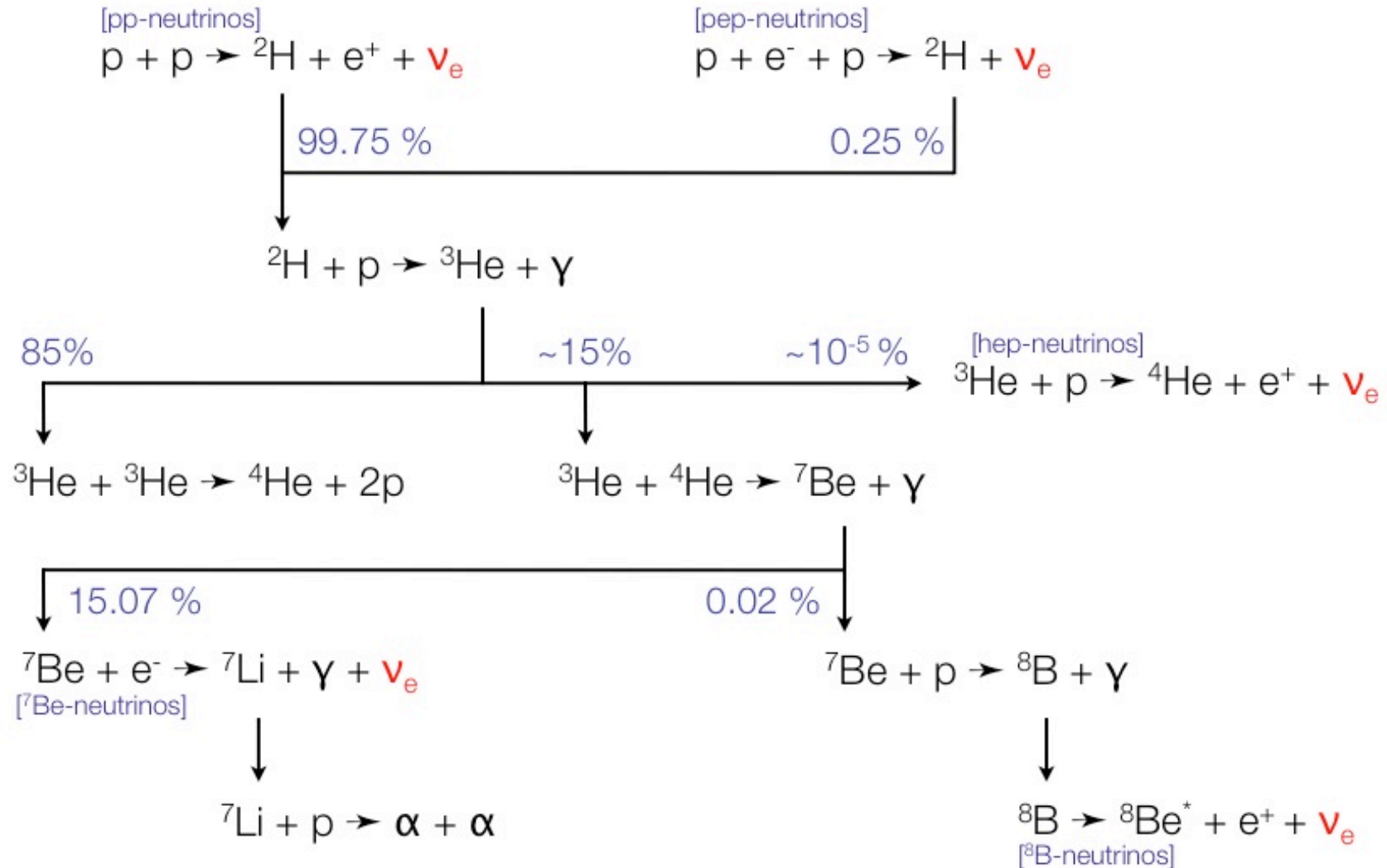
$$s_{lab} = 2m_e E + m_e^2$$

**Figure 5.** Energy dependence of various neutrino reactions and corresponding event rates. ( $f_{e/N} = 1$  for reactions on nucleons,  $f_{e/N} = A/Z$  for reactions on electrons.)

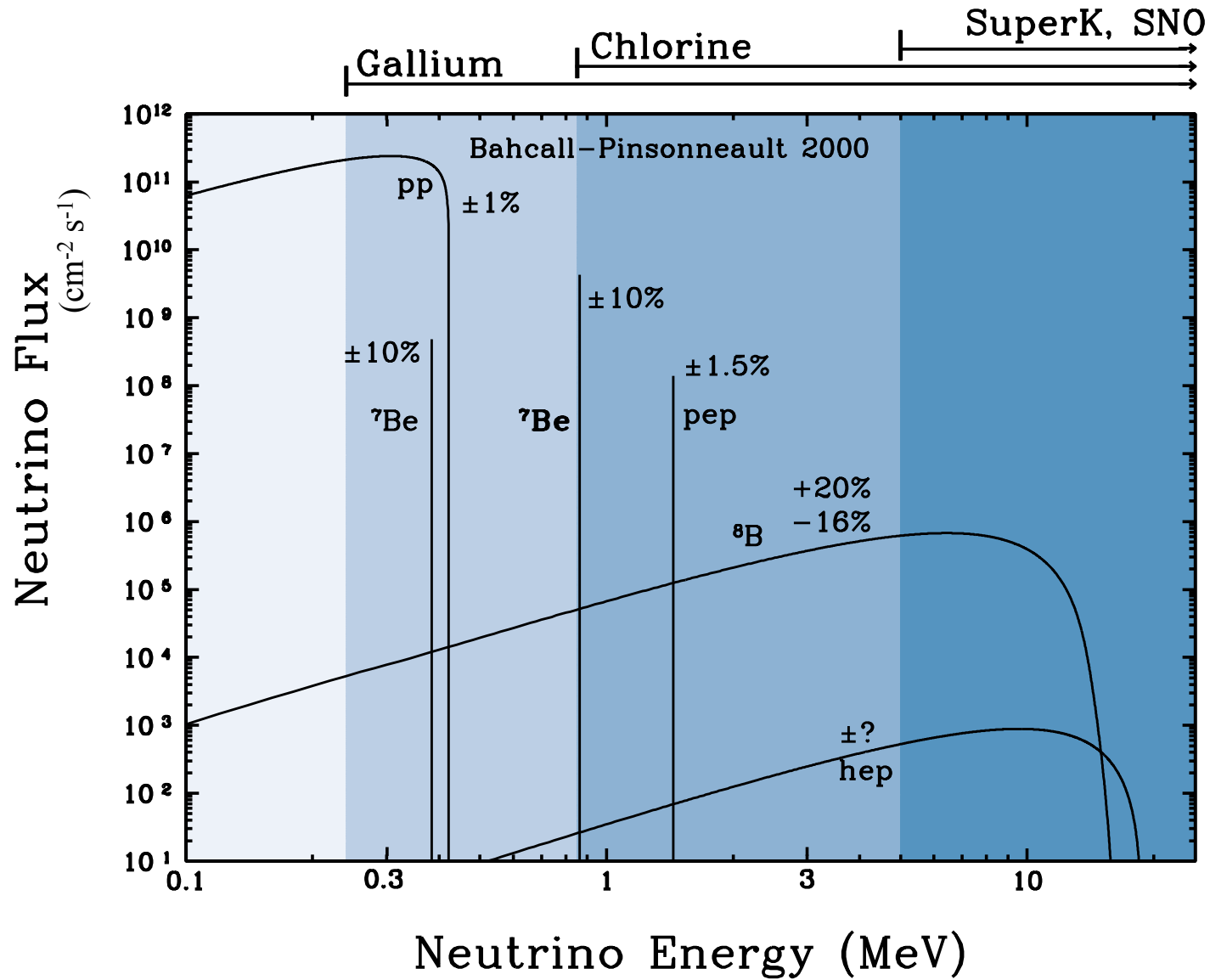
# Neutrino interaction inclusive cross section



# Neutrinos from the Sun

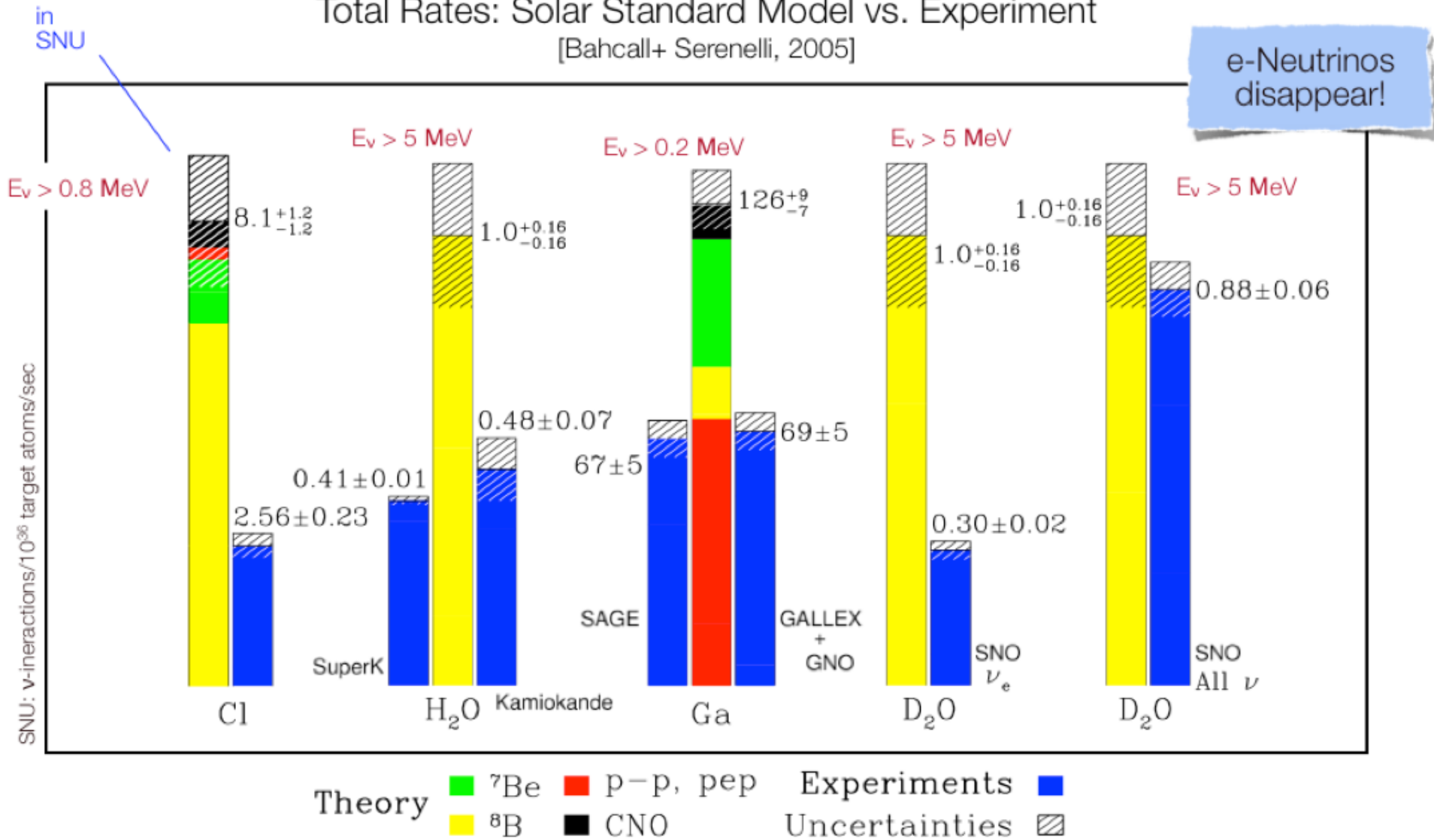


# Neutrinos from the Sun



# The “solar electron neutrino” problem

Total Rates: Solar Standard Model vs. Experiment  
[Bahcall+ Serenelli, 2005]



# Neutrino oscillation

Imagine we send a neutrino on a *long* journey. Suppose neutrino is created in the pion decay

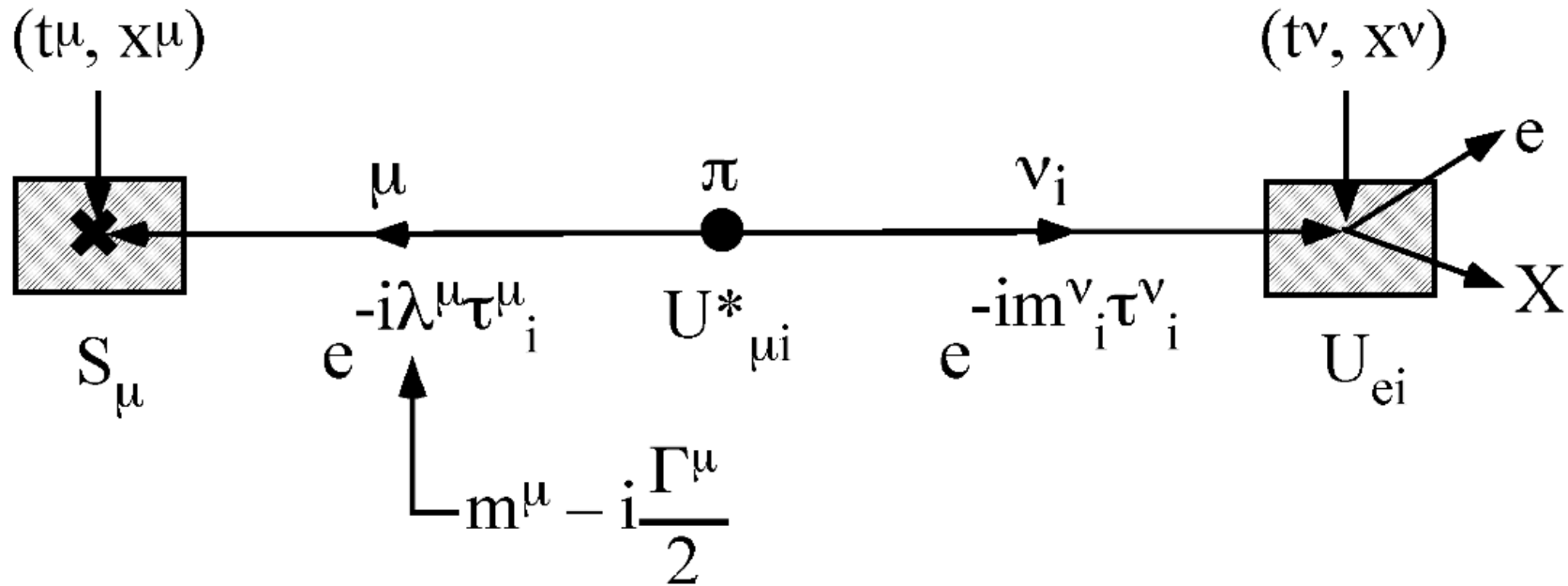
$$\pi \rightarrow \mu \nu_{\mu}$$

so that at birth it is a muon neutrino. Imagine that this neutrino interacts via  $W$  exchange in a distant detector, turning into a charged lepton. **If neutrinos have masses and leptons mix, then this charged lepton need not be a muon, but could be, say, a tau.**

- **Neutrinos have masses**  $\rightarrow$  there is some spectrum of neutrino mass eigenstates  $\nu_i$  w/ mass  $m_{\nu_i}$
- **Leptons mix**  $\rightarrow$  neutrinos of definite flavor,  $\nu_e$ ,  $\nu_{\mu}$ , and  $\nu_{\tau}$ , are not mass eigenstates  $\nu_i$ .

$$|\nu_{\alpha}\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \quad U = \begin{array}{c} \nu_1 \quad \nu_2 \quad \nu_3 \\ e \left[ \begin{array}{ccc} U_{e1} & U_{e2} & U_{e3} \\ \mu \left[ \begin{array}{ccc} U_{\mu1} & U_{\mu2} & U_{\mu3} \\ \tau \left[ \begin{array}{ccc} U_{\tau1} & U_{\tau2} & U_{\tau3} \end{array} \right] \end{array} \right] \end{array} \right] \end{array}$$

# Probability of neutrino oscillation



$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta; L, E) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re (U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \Delta m_{ij}^2 \frac{L}{4E} \right) \\ + 2 \sum_{i>j} \Im (U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left( \Delta m_{ij}^2 \frac{L}{2E} \right)$$

For full calculation see for instance Boris Kayser "Neutrino Oscillation Physics" <http://arxiv.org/abs/1206.4325>

# (Simplified) probability of neutrino oscillation

Let's forget the imaginary part of  $U$  (assume neutrinos and antineutrinos behave the same) and suppose only 2 flavors...

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

$$\begin{aligned} P(l \rightarrow l') &= 2 \cos^2 \theta \sin^2 \theta - 2 \cos^2 \theta \sin^2 \theta \cos \frac{m_j^2 - m_k^2}{2E} L \\ &= 2 \cos^2 \theta \sin^2 \theta \left( 1 - \cos \frac{m_j^2 - m_k^2}{2E} L \right) = 4 \cos^2 \theta \sin^2 \theta \sin^2 \left( \frac{m_j^2 - m_k^2}{4E} L \right) \\ &= \sin^2 2\theta \sin^2 \left( \frac{m_j^2 - m_k^2}{4E} L \right) \end{aligned}$$



# (Simplified) probability of neutrino oscillation

... and calculate!

$$\frac{m_j^2 - m_k^2}{4E} L = \frac{\Delta m^2 [\text{eV}^2]}{4 \times 10^6 E [\text{MeV}] \hbar c} \frac{L}{197 \times 10^6 [\text{eV}] \times 10^{-15} [\text{m}]} \\ = 1.27 \frac{\Delta m^2 [\text{eV}^2] L [\text{m}]}{E [\text{MeV}]} = 1.27 \frac{\Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]}$$

Being able to observe oscillations implies **phase variation**  $\sim 1$ .

Given L and E, accessible range is thus  **$\Delta m^2 [\text{eV}^2] > E [\text{GeV}] / L [\text{km}]$**

<b>Sorgente</b>	<b>E</b>	<b>L</b>	<b><math>\Delta m^2 [\text{eV}^2]</math></b>
<b>Reattori</b>	<b>1 - 10 MeV</b>	<b>10 m - 100 km</b>	
<b>Acceleratori</b>	<b>0.1 - 10 GeV</b>	<b>10 m - 100 km</b>	
<b>Atmosferici</b>	<b>1-10 GeV</b>	<b>10 - 10000 km</b>	
<b>Solari</b>	<b>0.1 - 10 MeV</b>	<b><math>1.5 \times 10^{11}</math> m</b>	

# Nobel Prize 2002

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba "*for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*" and the other half to Riccardo Giacconi "*for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources*".



Raymond  
Davis Jr.  
[Homestake]



Masatoshi  
Koshiba  
[Kamiokande]

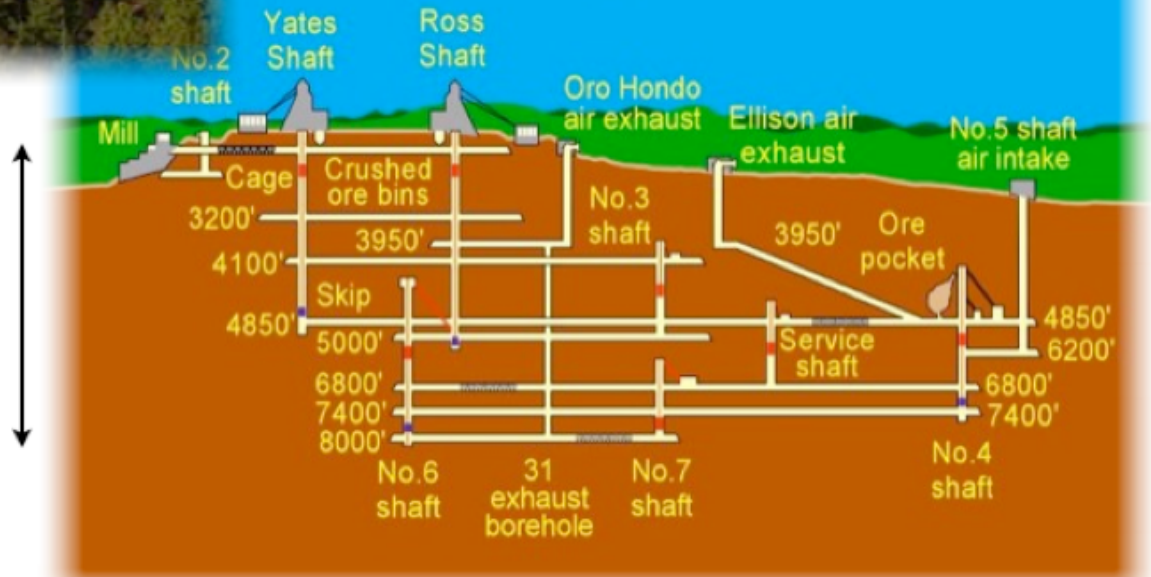


Riccardo  
Giacconi  
[X-Ray Sources]

# The Homestake experiment

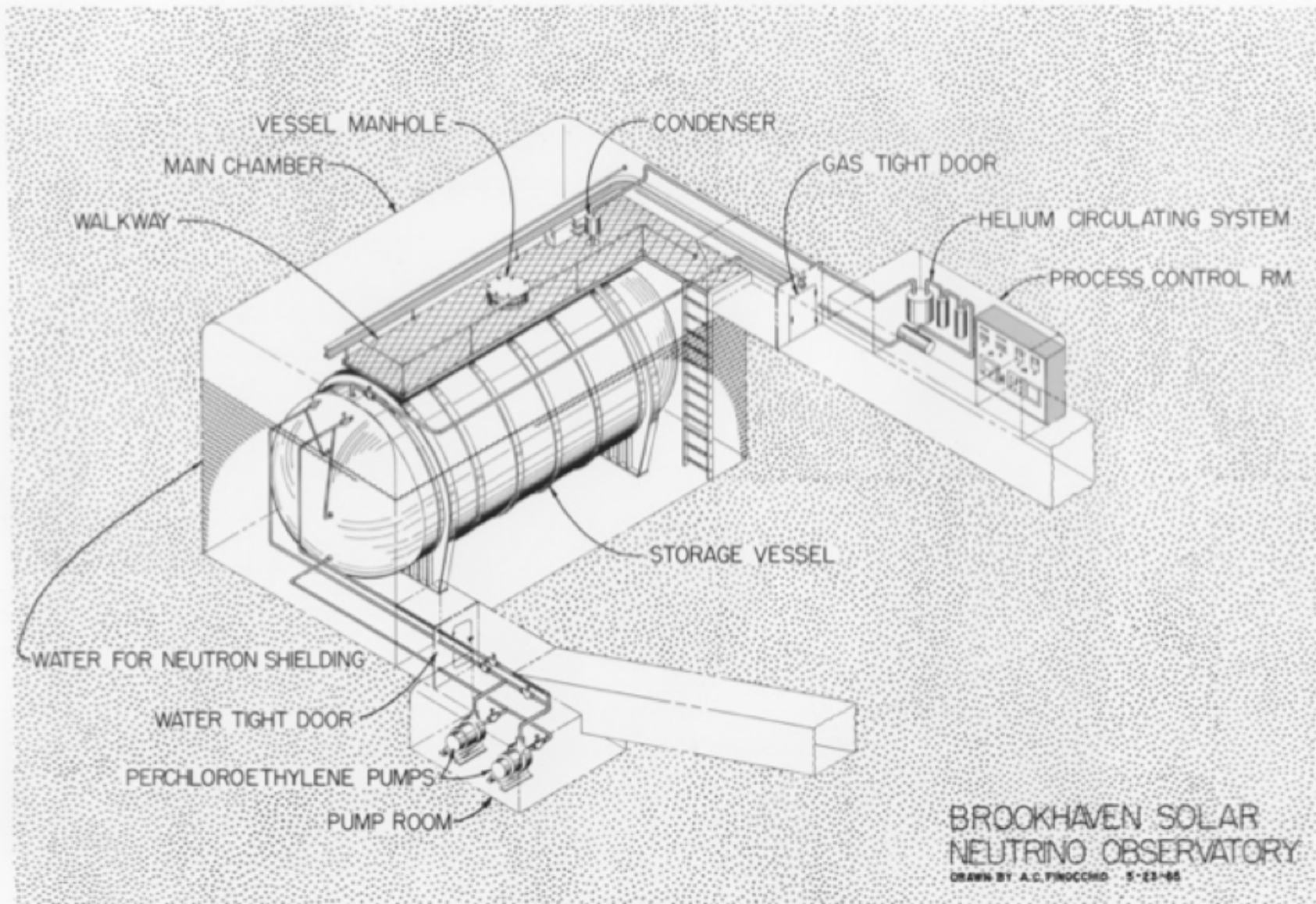


## General Homestake Mine Development



The Homestake Mine

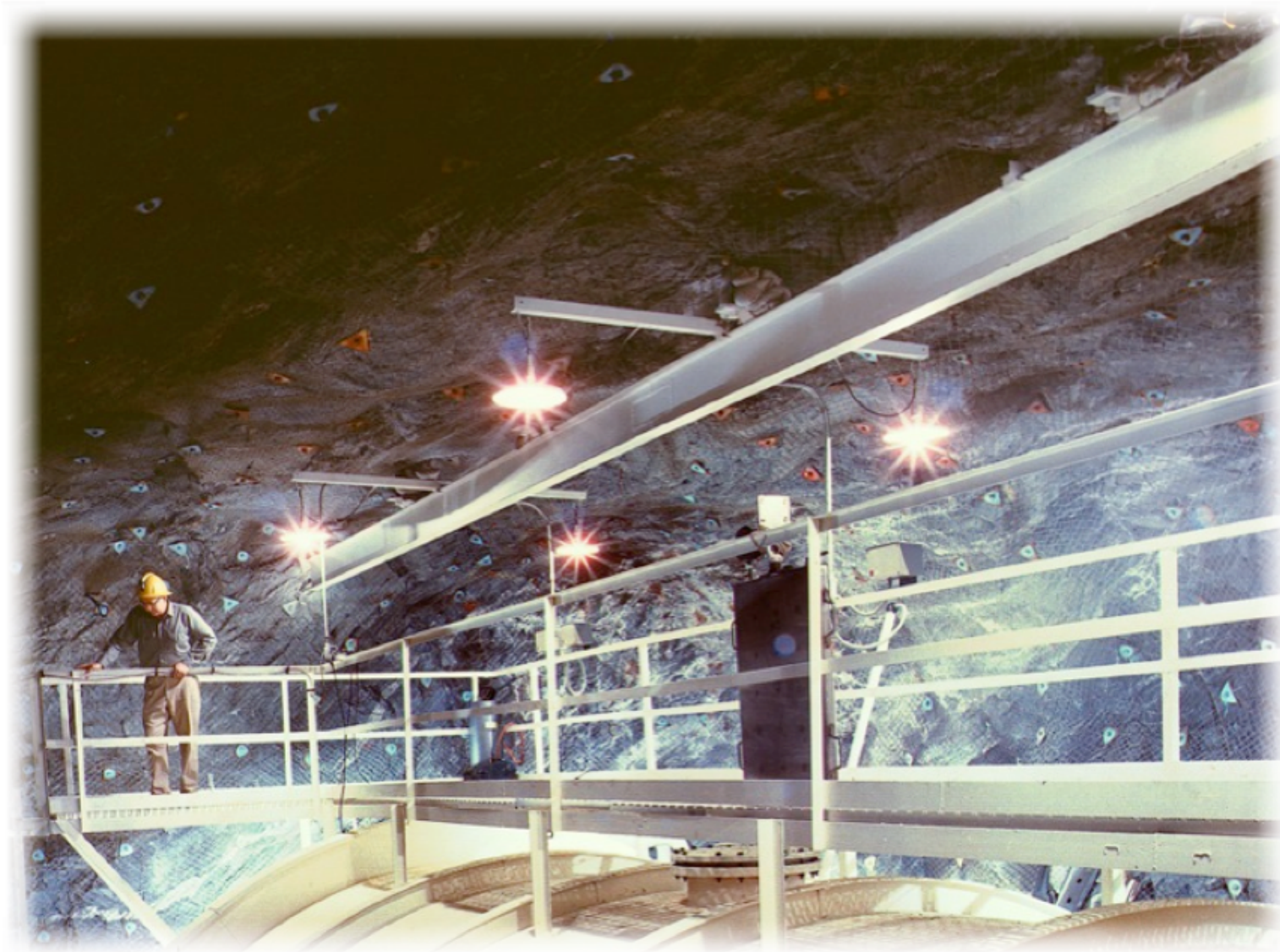
# The Homestake experiment



# The Homestake experiment



# The Homestake experiment



# The Homestake experiment

Neutrino capture:

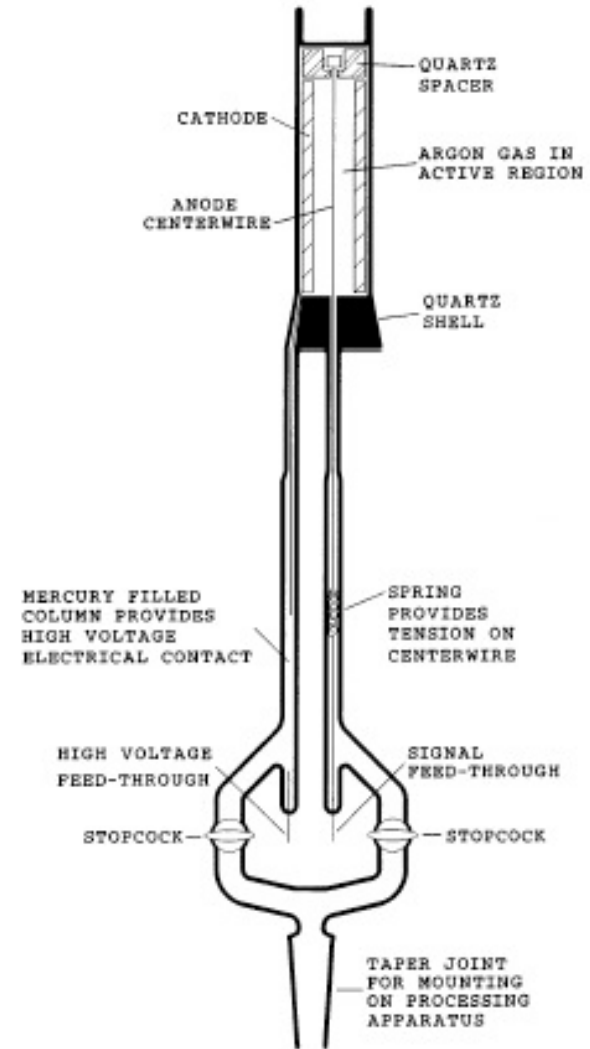


Lifetime: 35 days

Detection of  ${}^{37}\text{Ar}$  via  $e^-$ -capture [ ${}^{37}\text{Ar}(e, \nu_e){}^{37}\text{Cl}$ ];  $\tau \approx 35$  days results in Auger-electron @ 2.82 keV which after extraction is detected in proportional counter

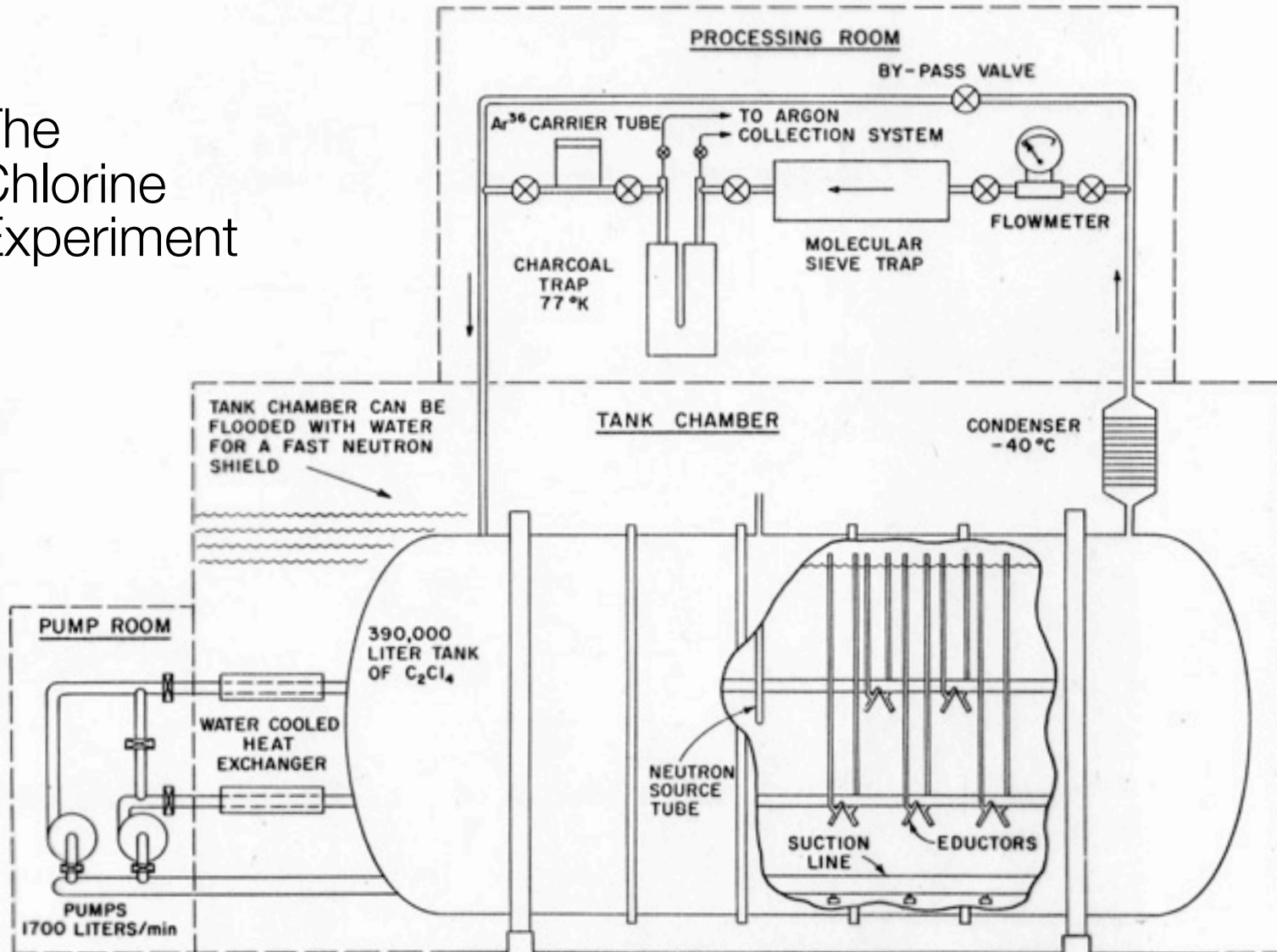
## Experimental details:

- 615 tons of  $\text{C}_2\text{Cl}_4$
- Threshold: 814-keV threshold
- Bubble He gas through to extract Ar [every 2-3 month]
- Ar trapped in cold trap
- Proportional Counter filled with Ar gas (7% methane)
- Important:  ${}^{37}\text{Cl}$  is 24% abundant.



# The Homestake experiment

## The Chlorine Experiment





# The Homestake experiment

Some *very approximate* numbers ...

- 615 tons  $C_2Cl_4$  (Tetrachloroethelene)
- About  $5 \times 10^{29}$  Chlorine Atoms ( $^{37}Cl$ )
- Prediction:  $8 \times 10^{-36}$   $\nu$ -reactions/atom/sec  
i.e.: about 60  $^{37}Ar$ -atoms/month;  
but: half-life = 35 days  $\rightarrow$  30 atoms/month

*6 Atoms/Molecule*

- Expect: 60 atoms every 2 month out of  
ca.  $10^{30}$  Tetrachloroethelene molecules

- After 25 years:

Expectation:  $\sim 5000$   $^{37}Ar$ -Atoms expected

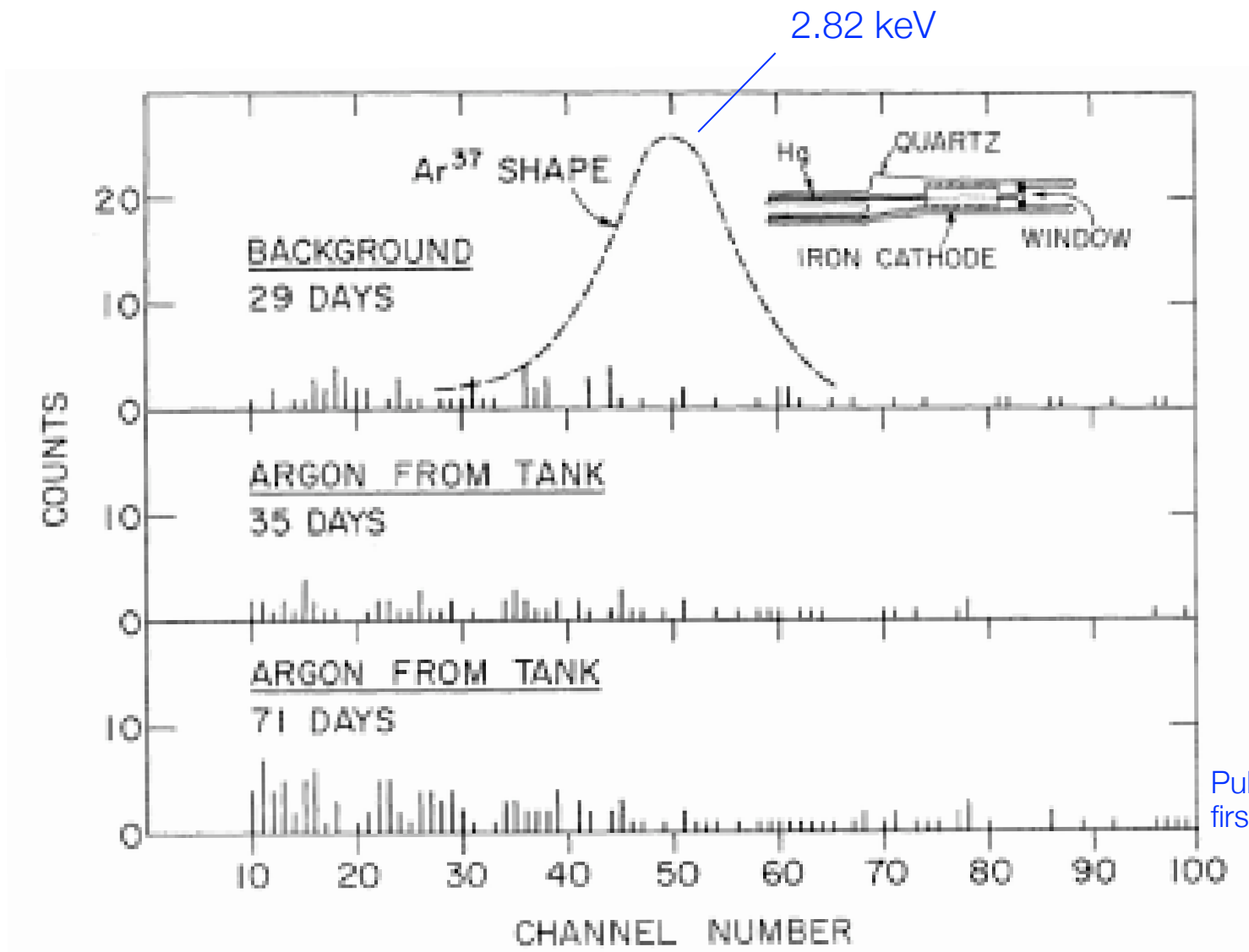
Observation:  $\sim 2200$   $^{37}Ar$ -Atoms produced

[875 counted; 776 after background subtraction]

*$^{37}Ar$ -Extraction  
Efficiency:  $\sim 95\%$*

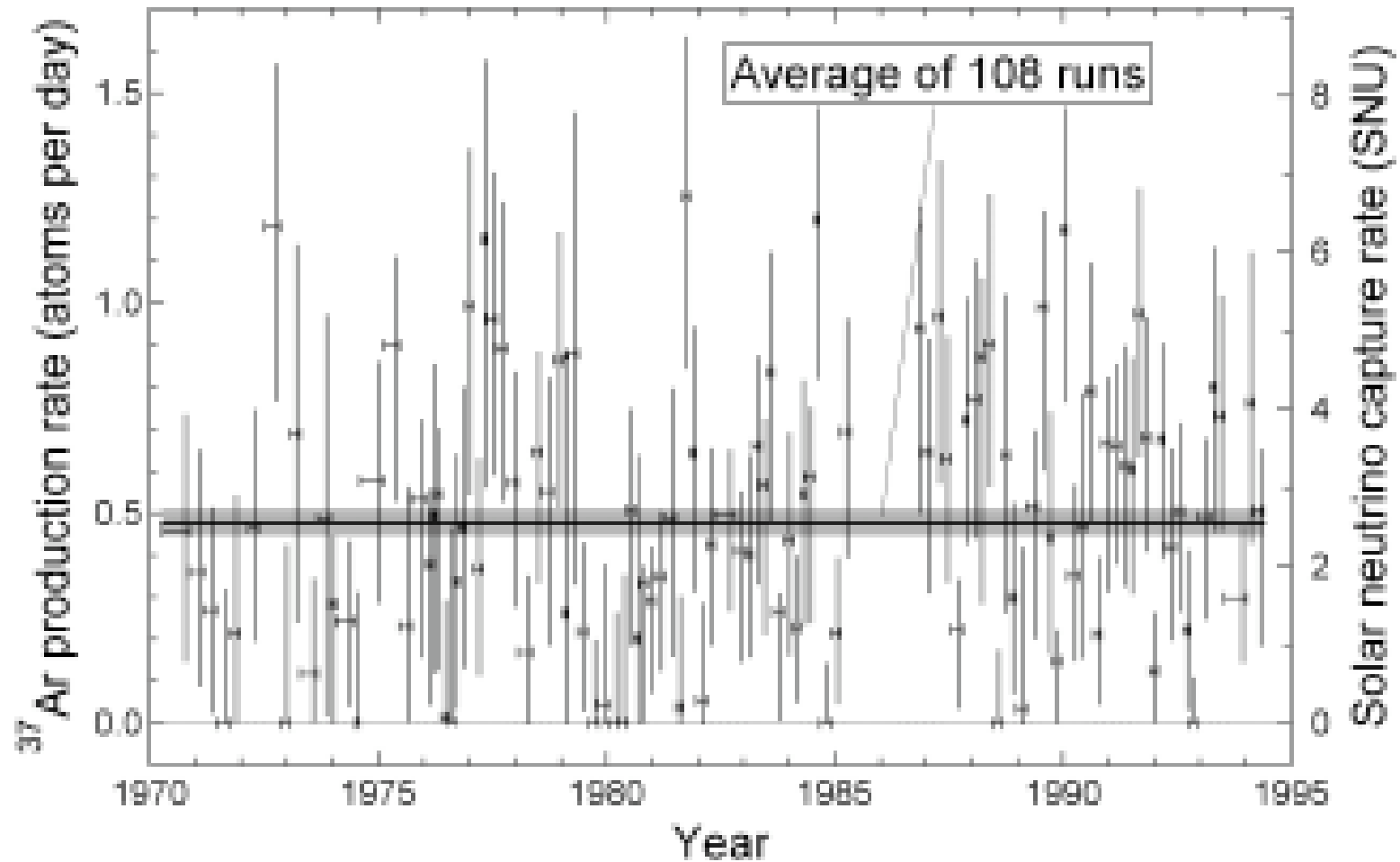
*$^{37}Ar$ -Detection  
Efficiency:  $\sim 45\%$*

# The Homestake experiment

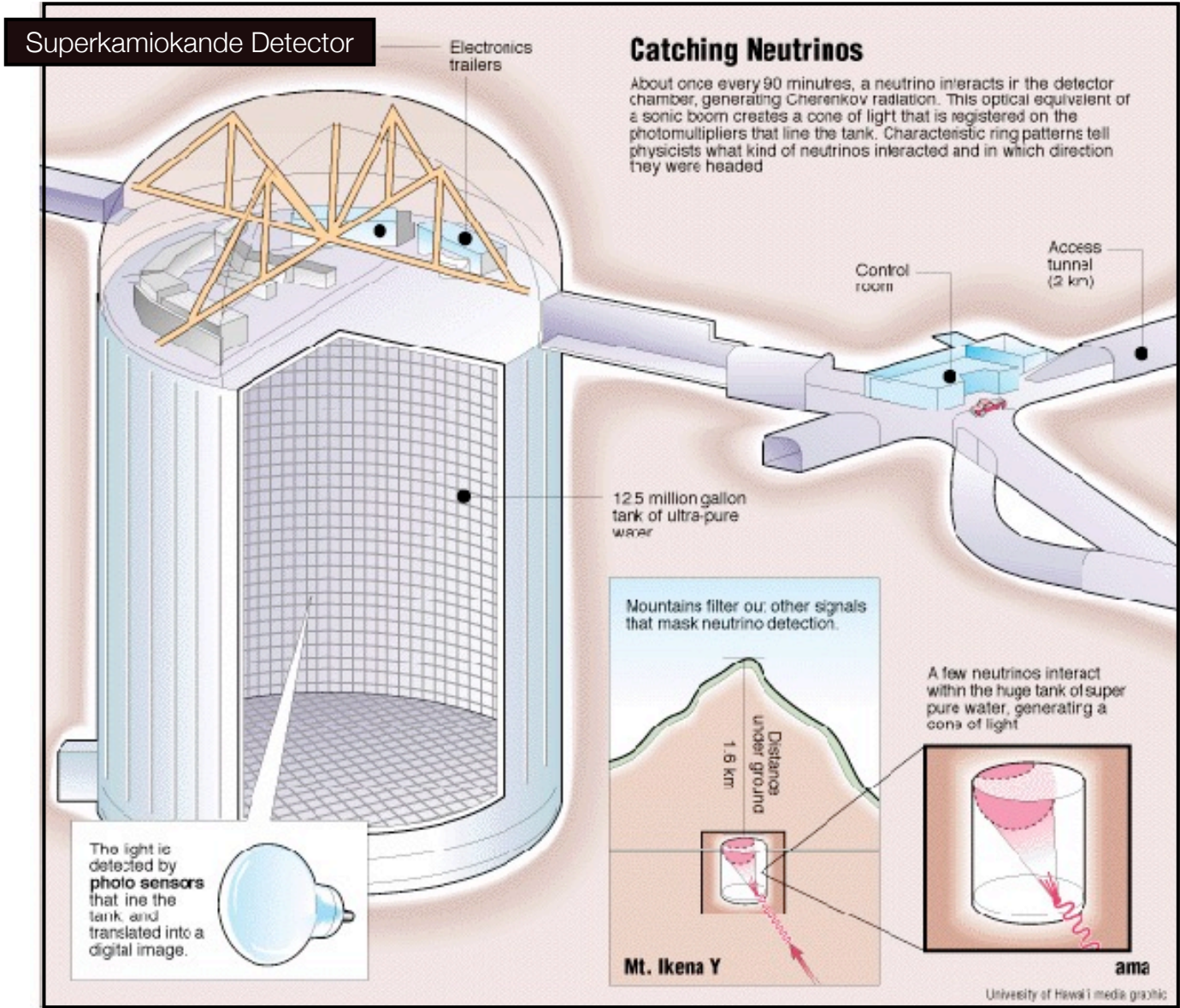


# The Homestake experiment

Result of 25 years of running  
[after implementation of rise time counting]



# Super-Kamiokande



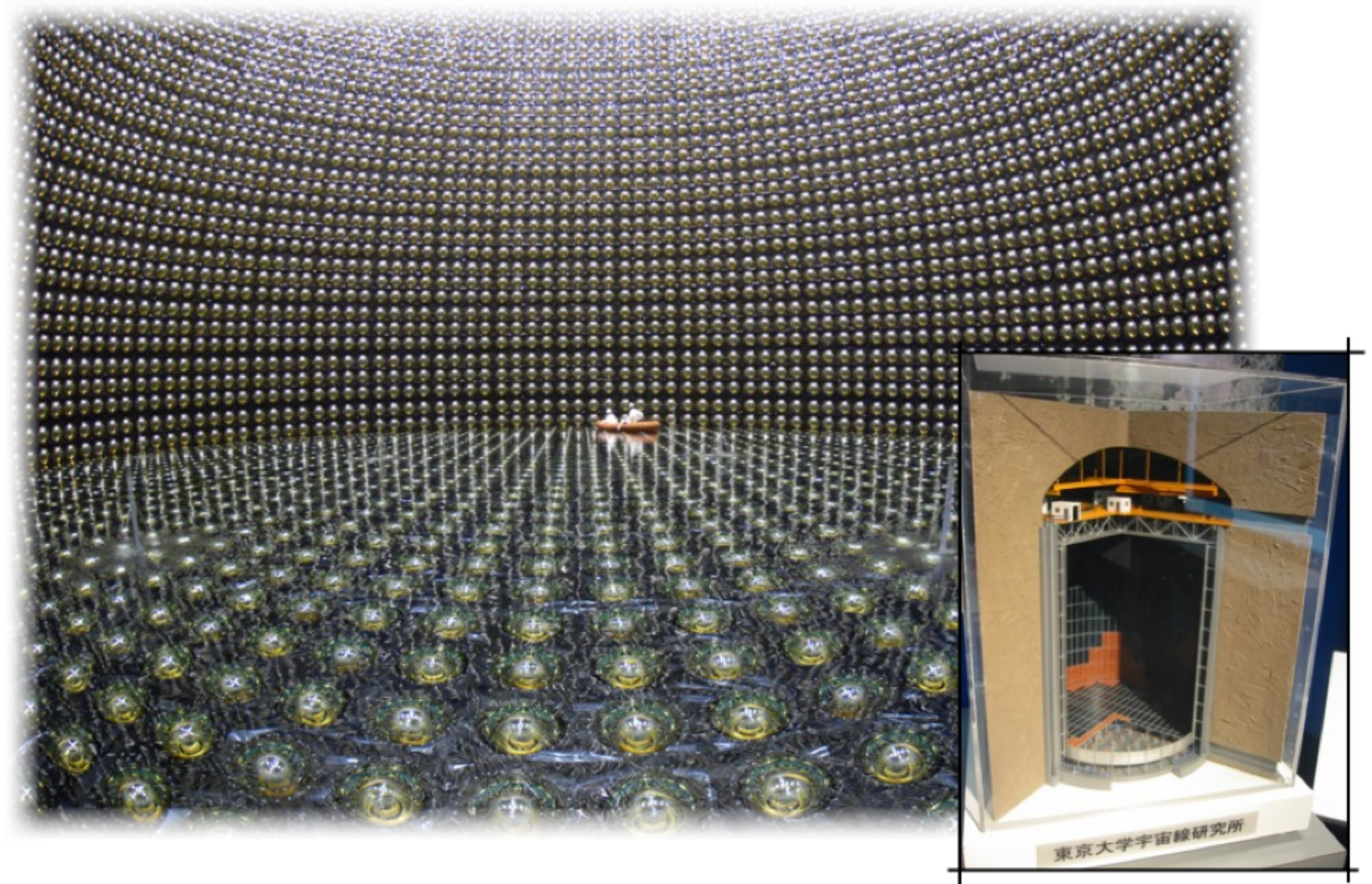
Water tank  
1.6 km below ground

50 Million liter  
ultra-pure water

1 Neutrino-interaction  
every 1.5 hours

Neutrino detection  
via Cherenkov light

# Super-Kamiokande



# Super-Kamiokande



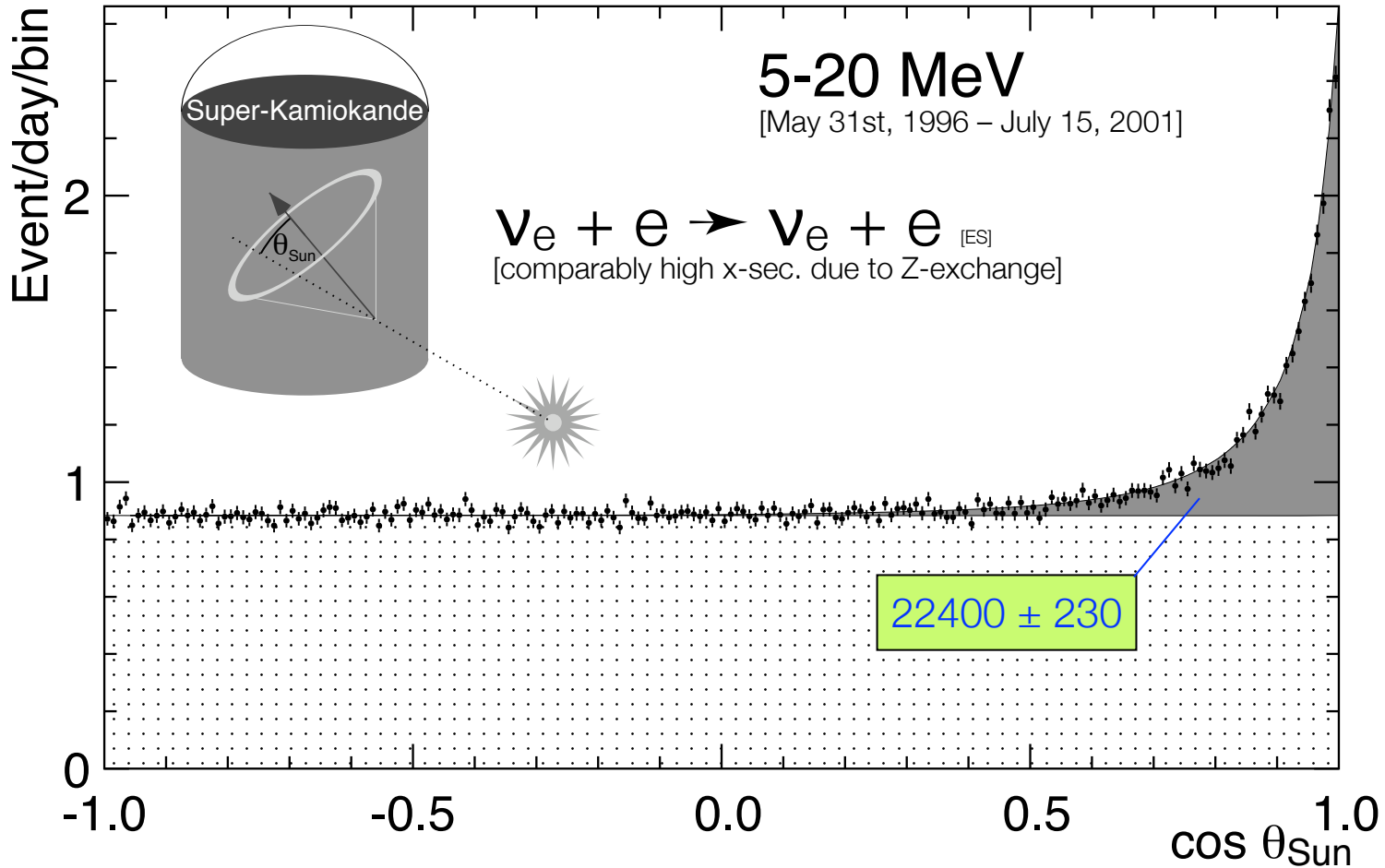
## Mounting of Photomultiplier Tubes

Total: 11,146 20" pmts  
1,885 8" pmts

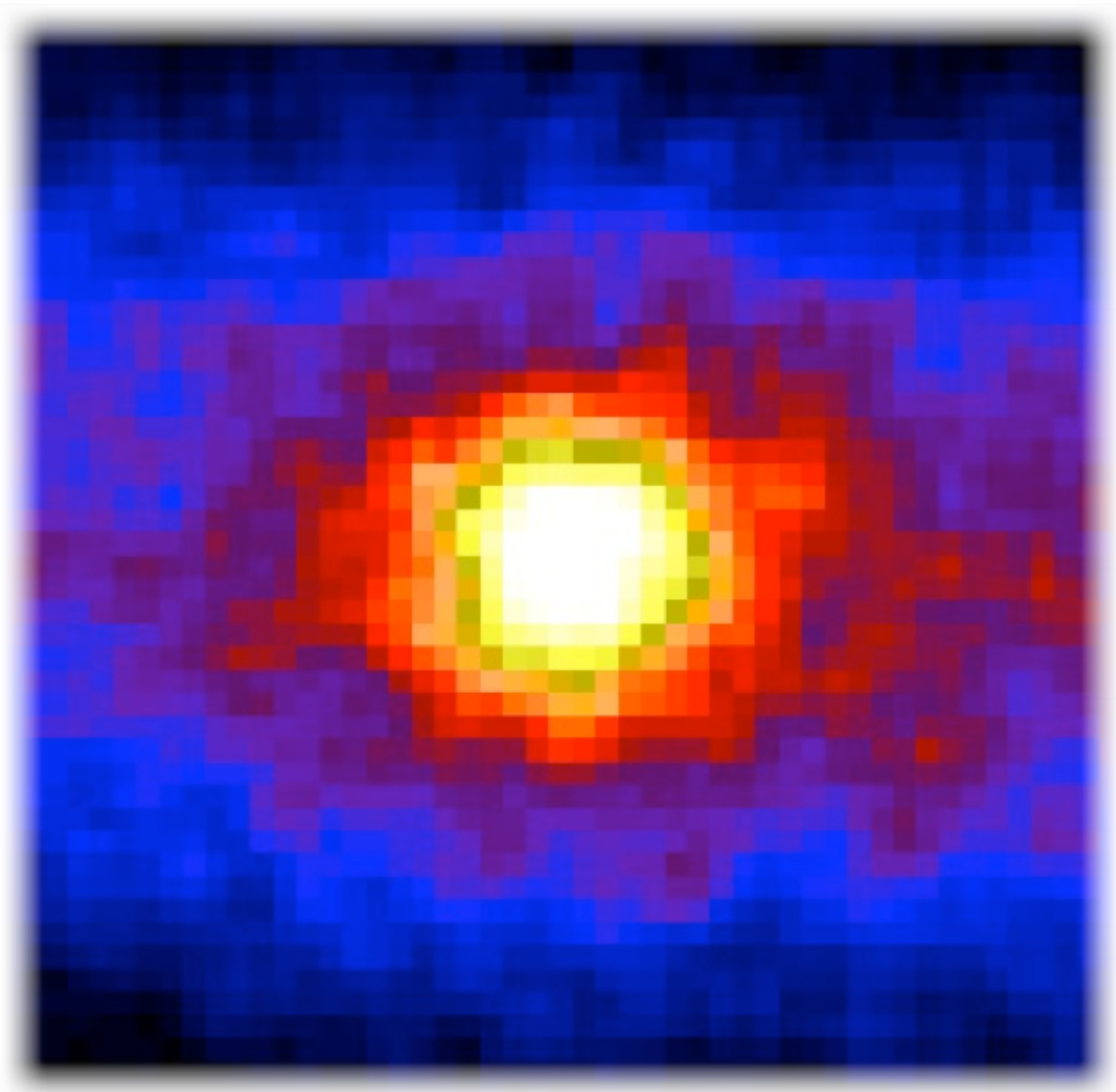


# Super-Kamiokande

SK-I:  ${}^8\text{B}$  Solar Neutrino Flux



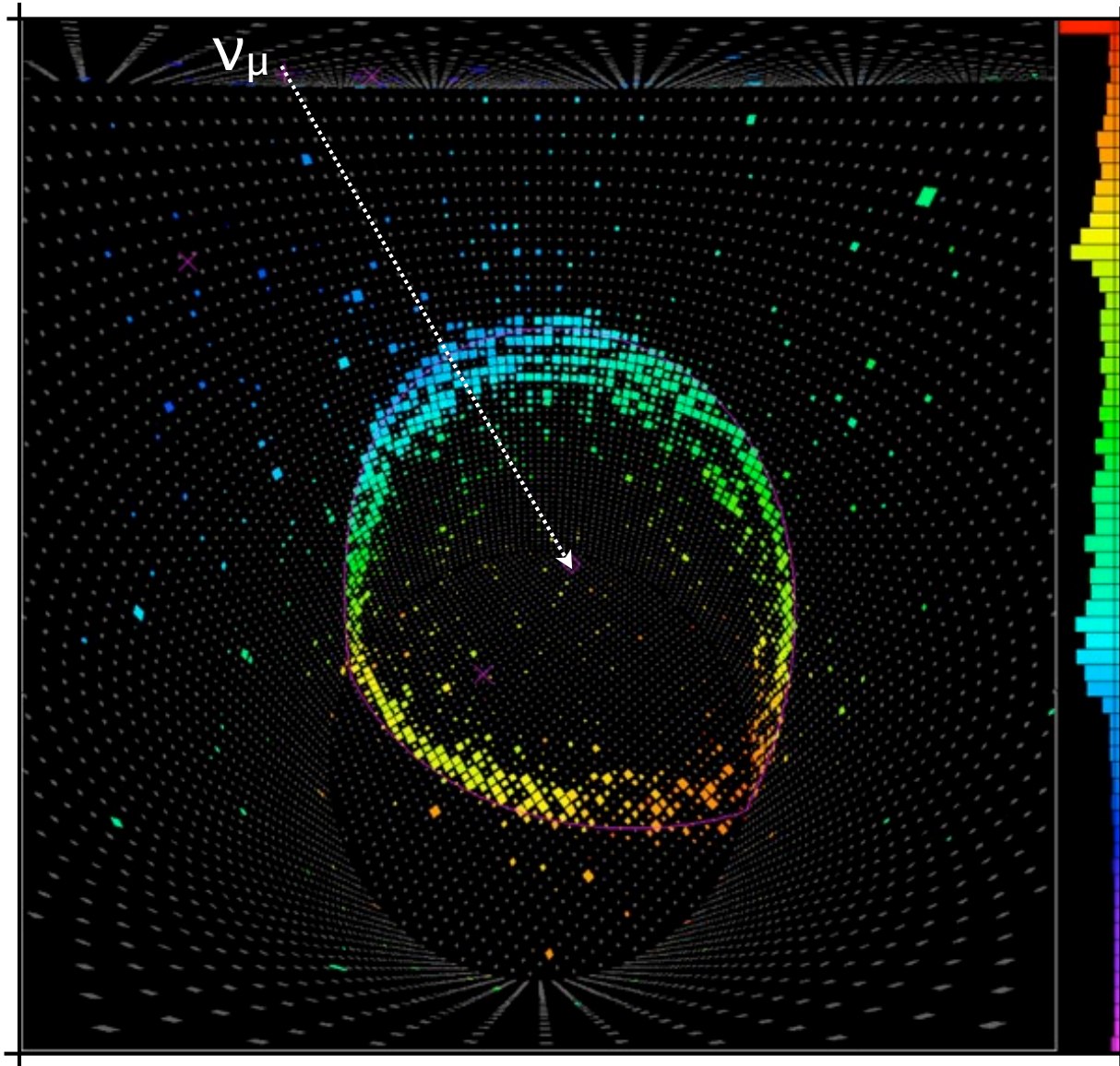
# Super-Kamiokande



The sun seen  
through the earth  
in neutrino light



# Super-Kamiokande



## Muon event

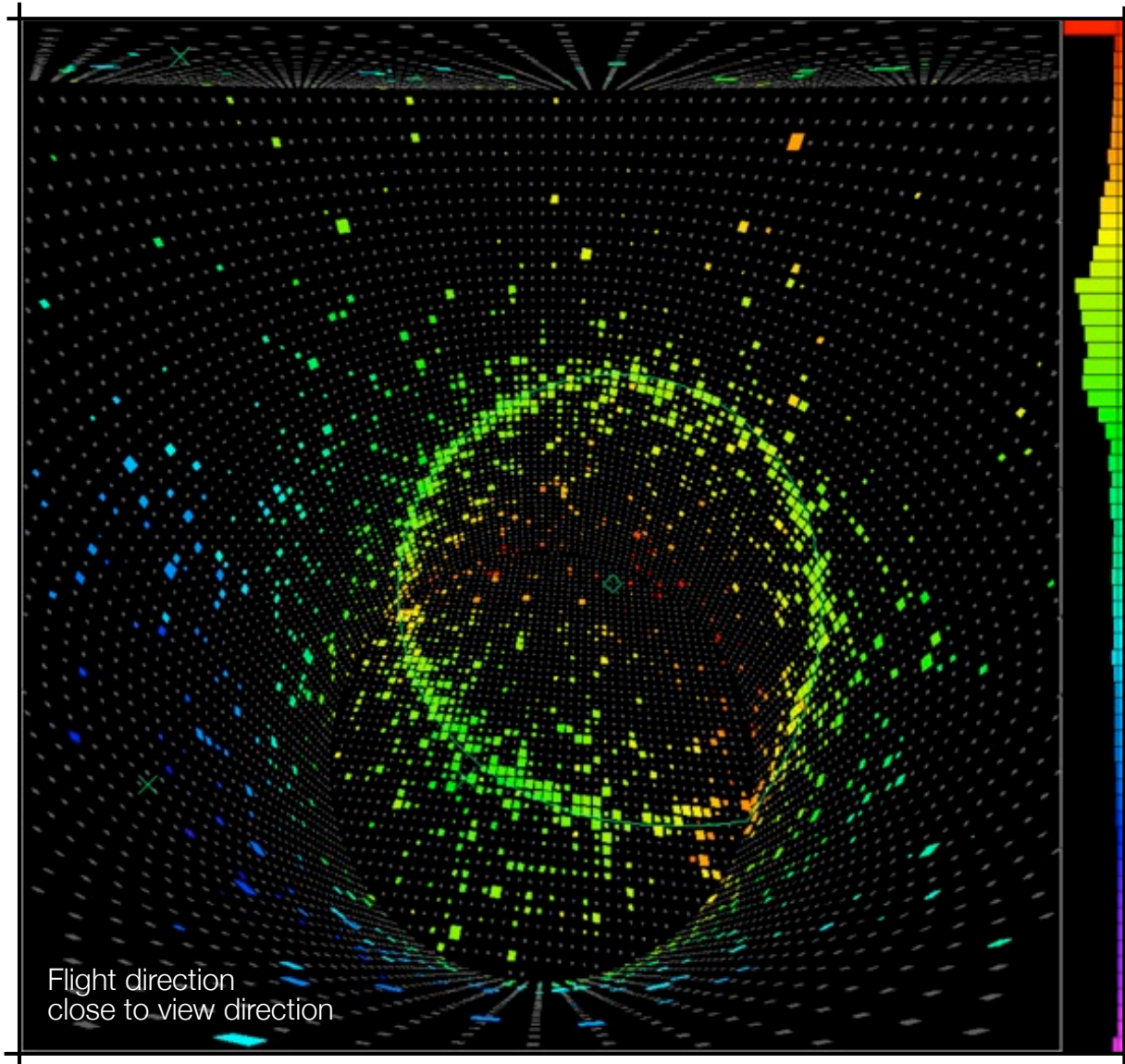
[603 MeV]

Observation of  
clean Cherenkov ring  
with sharp edges

Flight direction from  
timing measurements  
[blue: early; red: late]

Energy from amount  
of light observed in PMTs

# Super-Kamiokande



## Electron event

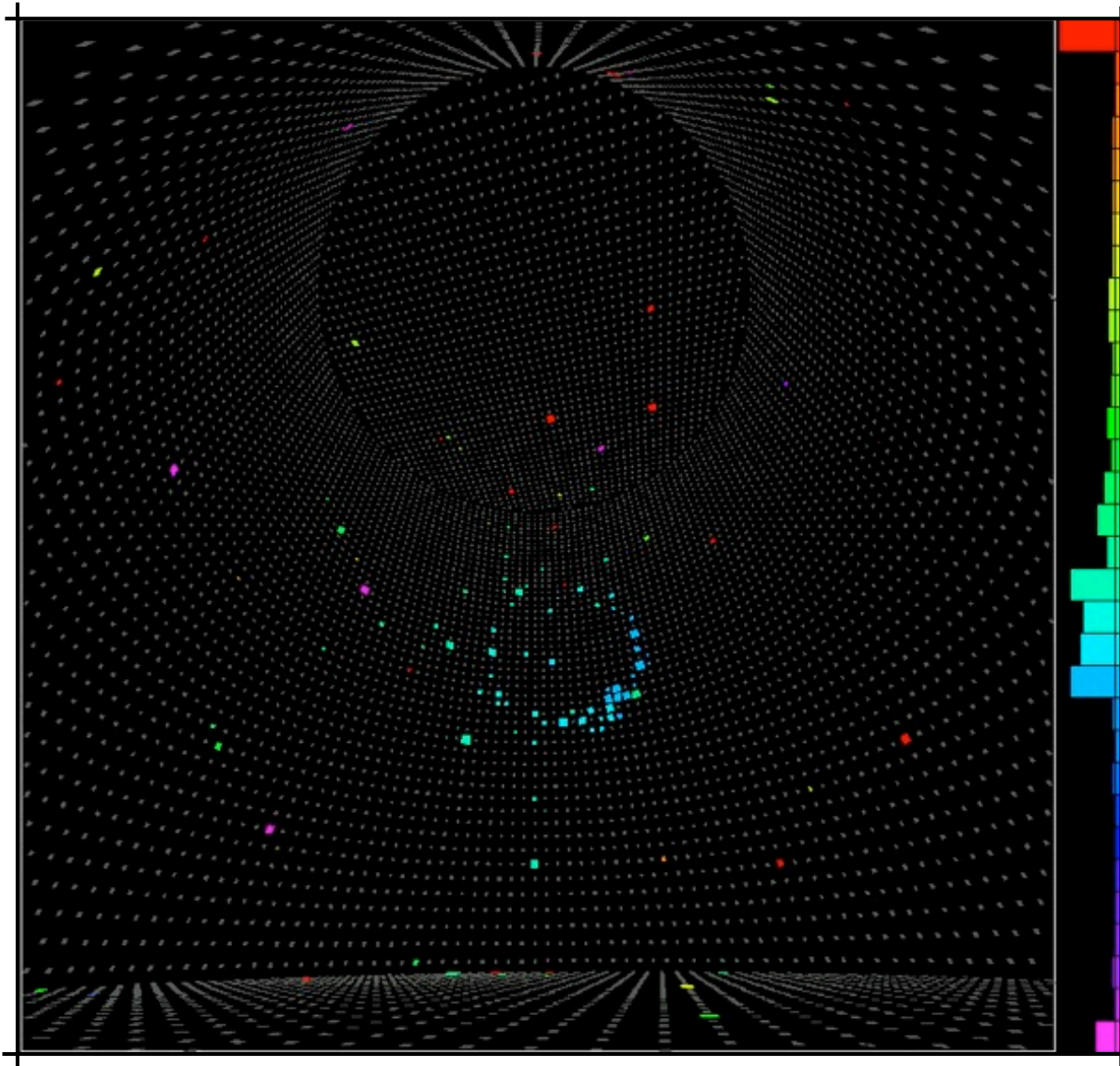
[492 MeV]

Observation of  
Cherenkov ring  
with fuzzy edge  
[from e.m. shower]

Flight direction from  
timing measurements  
[blue: early; red: late]

Energy from amount  
of light observed in PMTs

# Super-Kamiokande



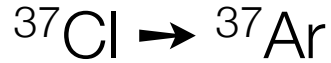
Solar neutrino  
[12.5 MeV]

Unusually nice,  
well-defined

Flight direction from  
timing measurements  
[blue: early; red: late]

Energy from amount  
of light observed in PMTs

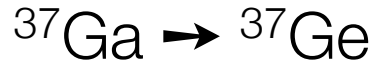
# Other solar neutrino experiments



[Homestake]

Exp:  $\sim 2.6$  SNU

BS05:  $\sim 8.1$  SNU



[Gallex, GNO, Sage]

Exp:  $\sim 70$  SNU

BS05:  $\sim 126$  SNU



[Kamikande, SNO]

Exp:  $\sim 2.4$  SNU

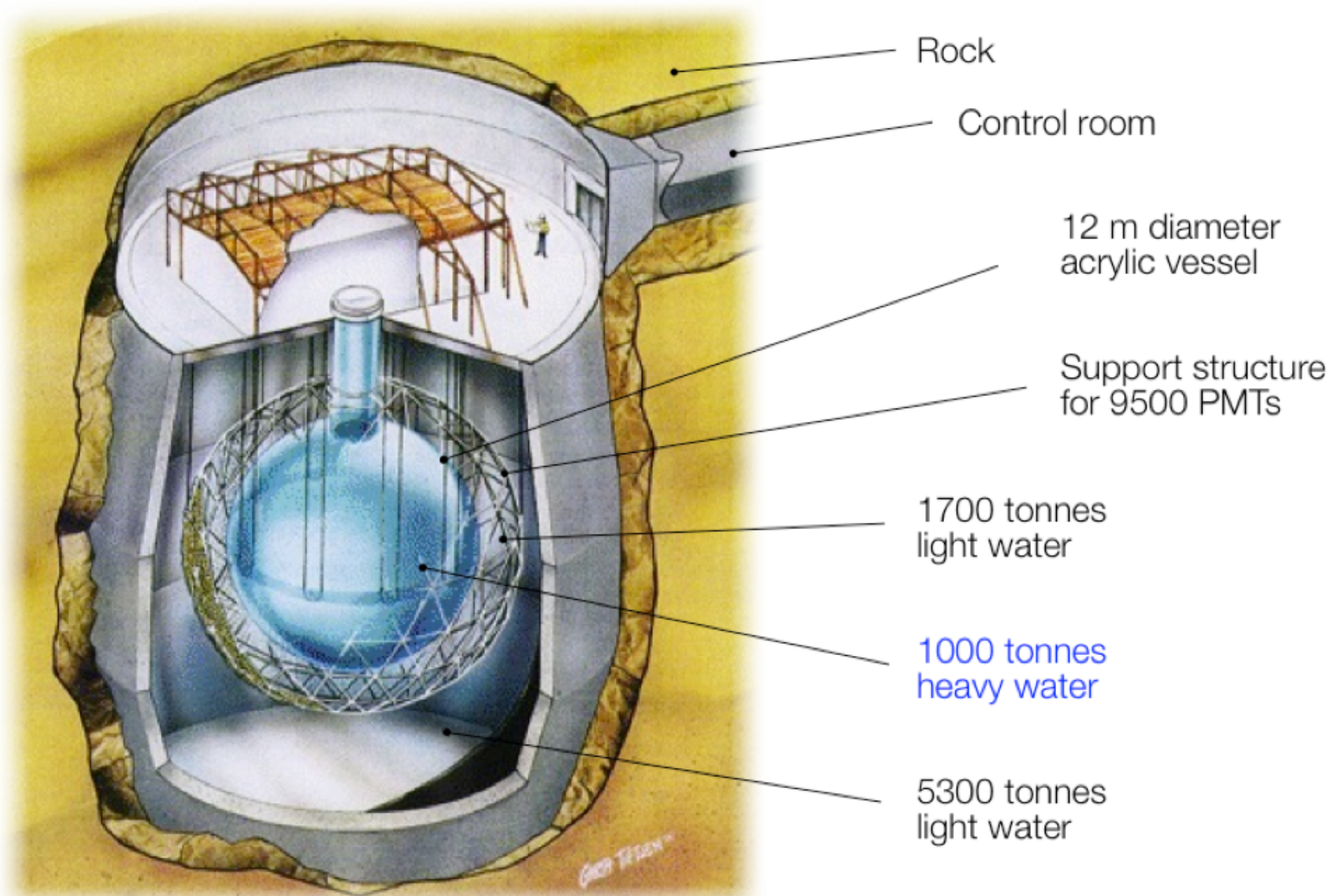
BS05:  $\sim 5.7$  SNU

$\nu_e$  only

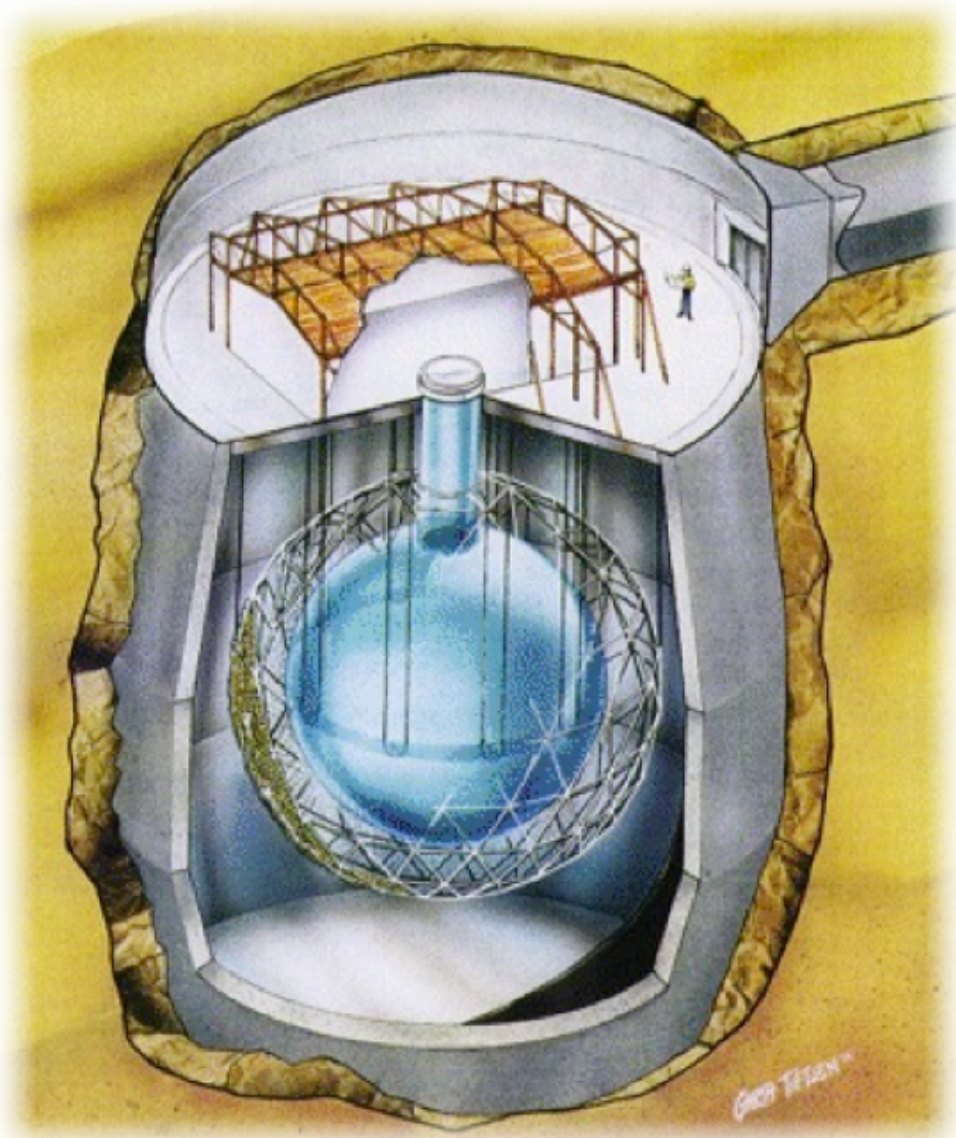
	$^{37}\text{Cl} \rightarrow ^{37}\text{Ar}$ (SNU)	$^{71}\text{Ga} \rightarrow ^{71}\text{Ge}$ (SNU)	$^8\text{B } \nu$ flux ( $10^6 \text{cm}^{-2}\text{s}^{-1}$ )
Homestake			
(CLEVELAND 98)[20]	$2.56 \pm 0.16 \pm 0.16$	—	—
GALLEX			
(HAMPEL 99)[21]	—	$77.5 \pm 6.2^{+4.3}_{-4.7}$	—
GNO			
(ALTMANN 05)[22]	—	$62.9^{+5.5}_{-5.3} \pm 2.5$	—
GNO+GALLEX			
(ALTMANN 05)[22]	—	$69.3 \pm 4.1 \pm 3.6$	—
SAGE			
(ABDURASHI...02)[23]	—	$70.8^{+5.3+3.7}_{-5.2-3.2}$	—
Kamiokande			
(FUKUDA 96)[24]	—	—	$2.80 \pm 0.19 \pm 0.33^\dagger$
Super-Kamiokande			
(HOSAKA 05)[25]	—	—	$2.35 \pm 0.02 \pm 0.08^\dagger$
SNO (pure D <sub>2</sub> O)			
(AHMAD 02)[4]	—	—	$1.76^{+0.06}_{-0.05} \pm 0.09^\ddagger$
—	—	—	$2.39^{+0.24}_{-0.23} \pm 0.12^\dagger$
—	—	—	$5.09^{+0.44+0.46*}_{-0.43-0.43}$
SNO (NaCl in D <sub>2</sub> O)			
(AHARMIM 05)[11]	—	—	$1.68 \pm 0.06^{+0.08}_{-0.09}^\ddagger$
—	—	—	$2.35 \pm 0.22 \pm 0.15^\dagger$
—	—	—	$4.94 \pm 0.21^{+0.38*}_{-0.34}$
BS05(OP) SSM [13]	$8.1 \pm 1.3$	$126 \pm 10$	$5.69(1.00 \pm 0.16)$
Seismic model [18]	$7.64 \pm 1.1$	$123.4 \pm 8.2$	$5.31 \pm 0.6$

[PDG 2008]

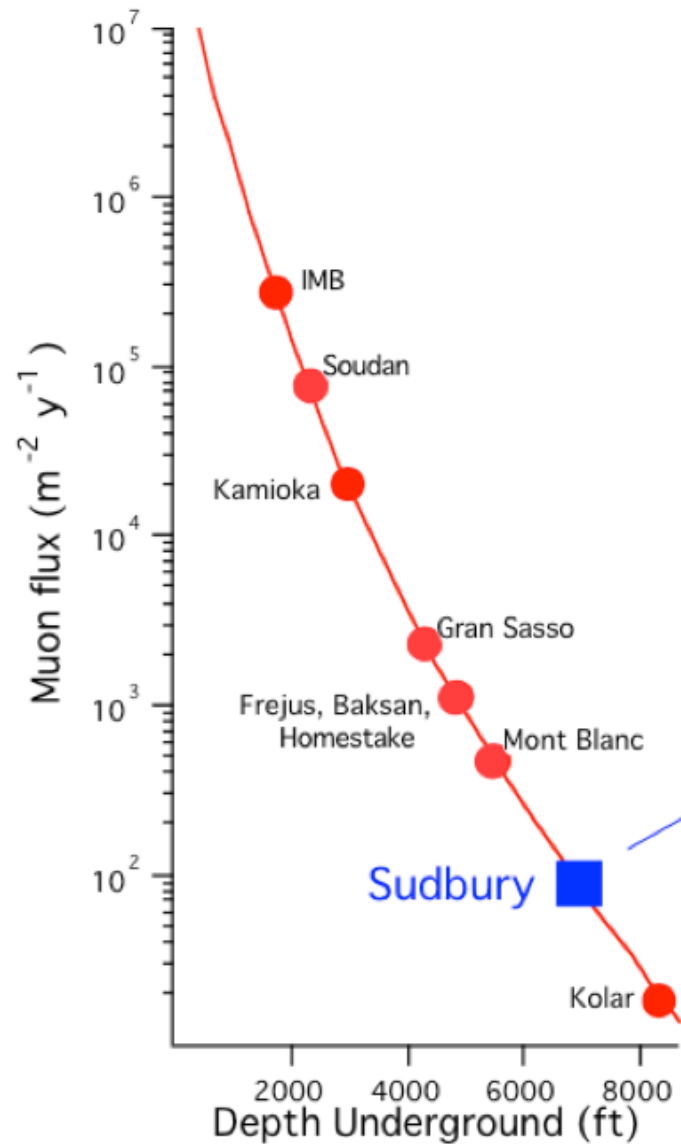
# The SNO experiment



# The SNO experiment

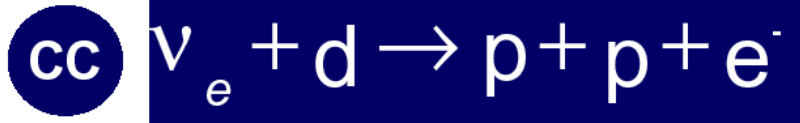


# The SNO experiment

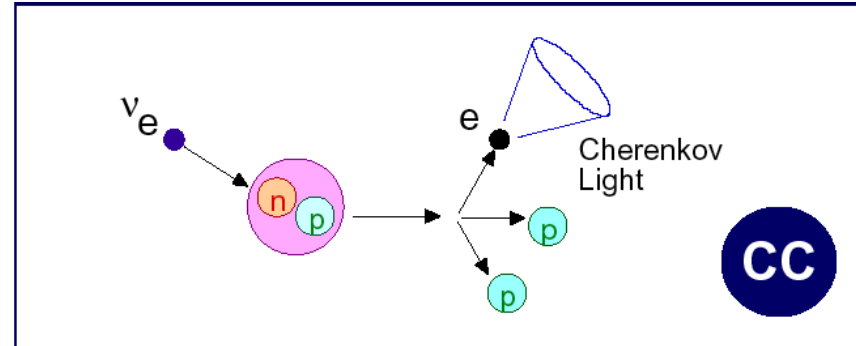


More than 2 km below ground  
Background:  $< 100 \mu/\text{day}$

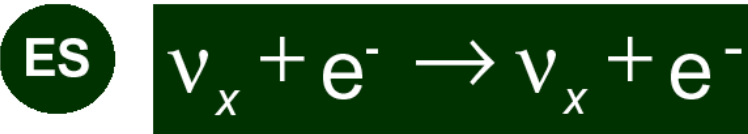
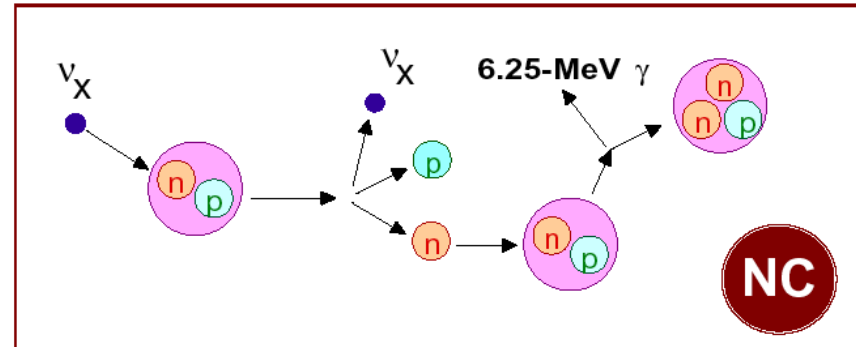
# The SNO experiment



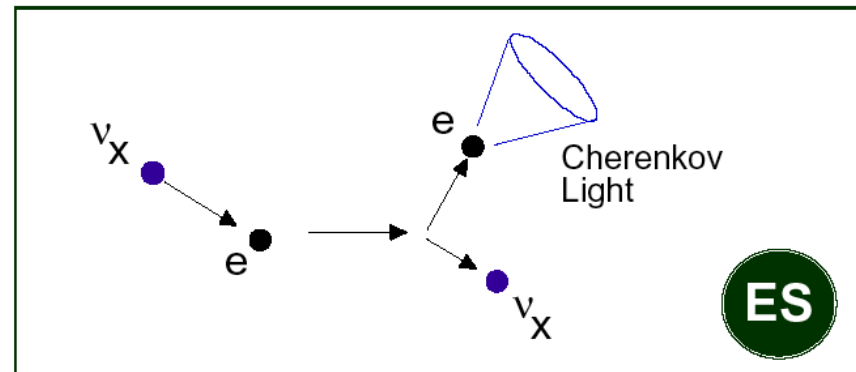
- Measurement of  $\nu_e$  energy spectrum
- Weak directionality:  $1 - 0.340 \cos\theta$



- Measure total  $^8\text{B}$   $\nu$  flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

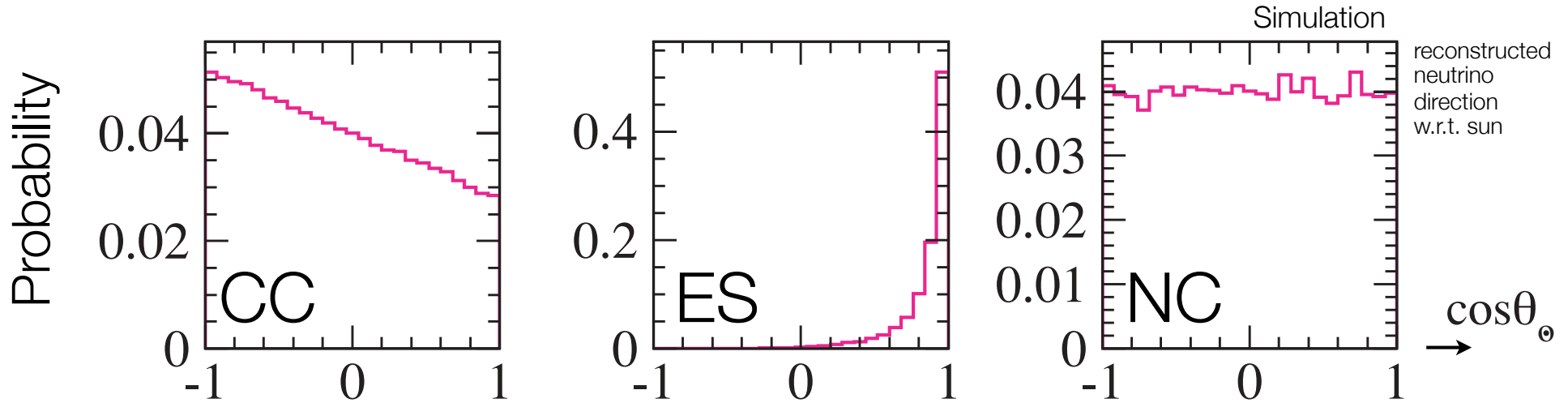


- Low Statistics
- $\Sigma\phi = \phi(\nu_e) + 0.154 \phi(\nu_\mu + \nu_\tau)$
- Strong directionality:  
 $\theta_e \leq 18^\circ$  ( $T_e = 10$  MeV)



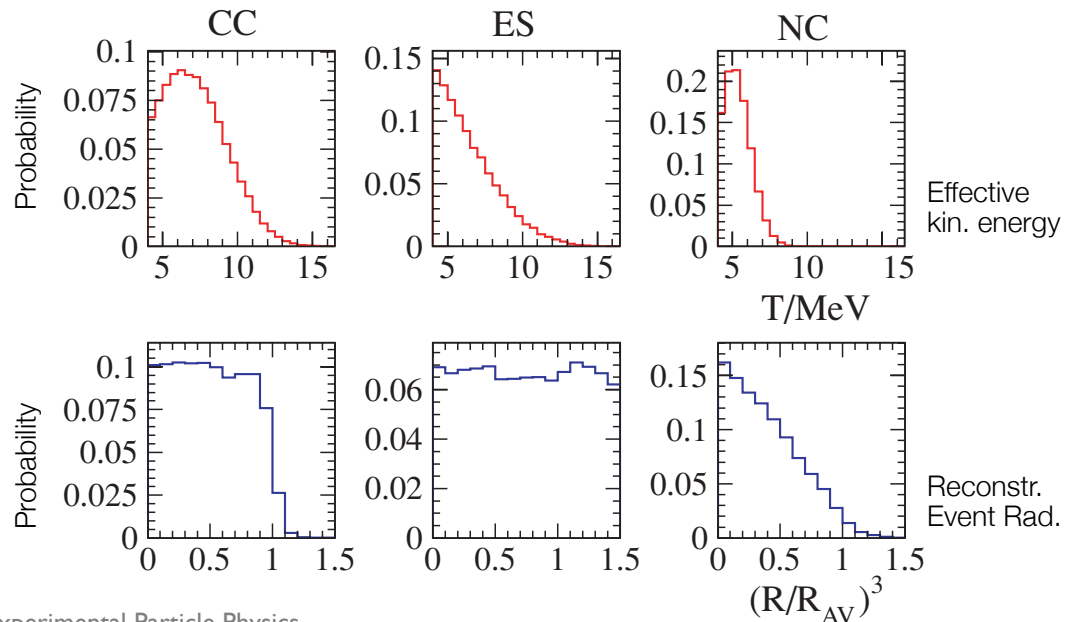


# The SNO experiment

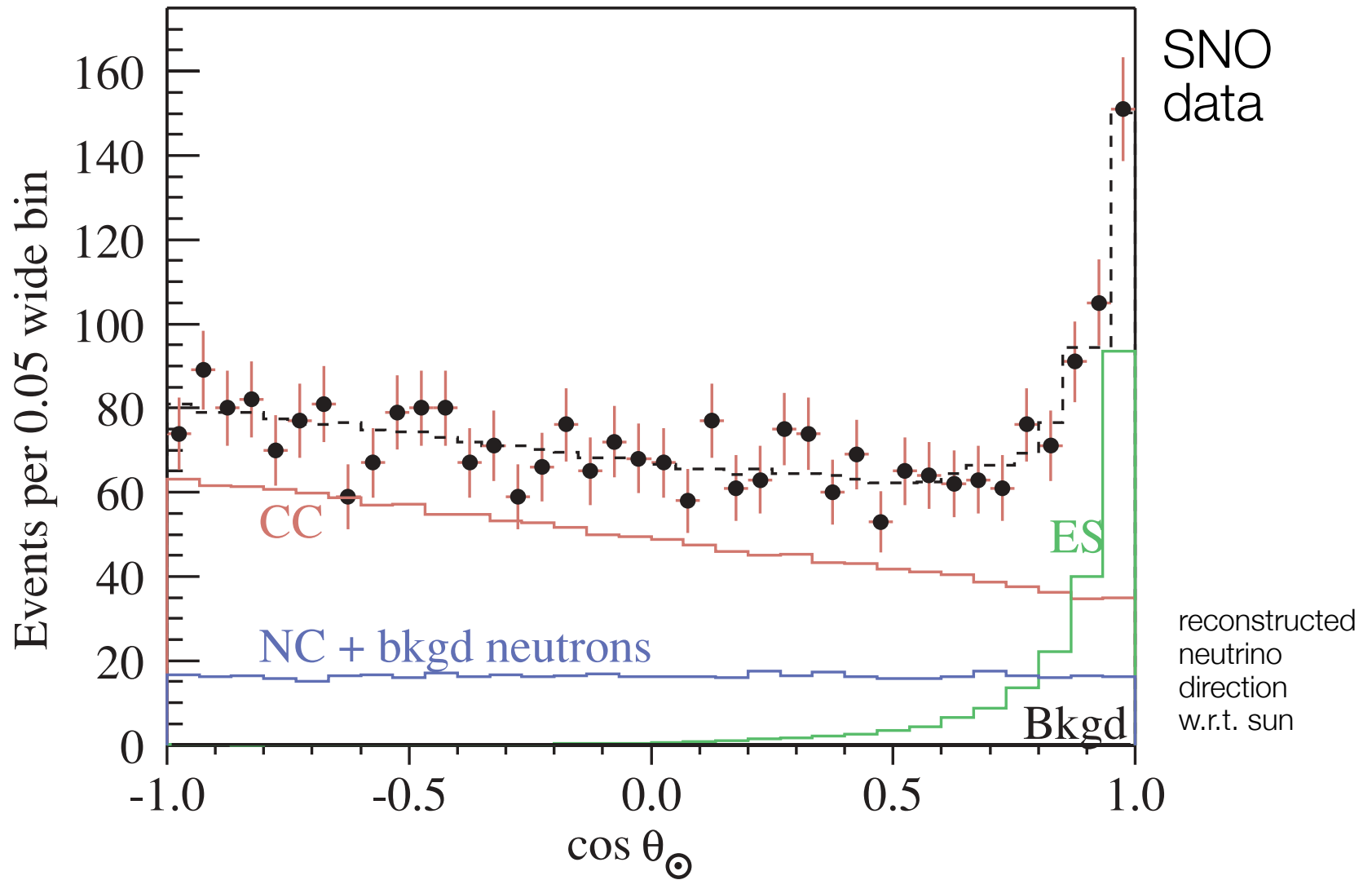


## Analysis strategy:

Determine size of CC, ES and NC signals via a fit of the data to probability distributions



# The SNO experiment



SNO data

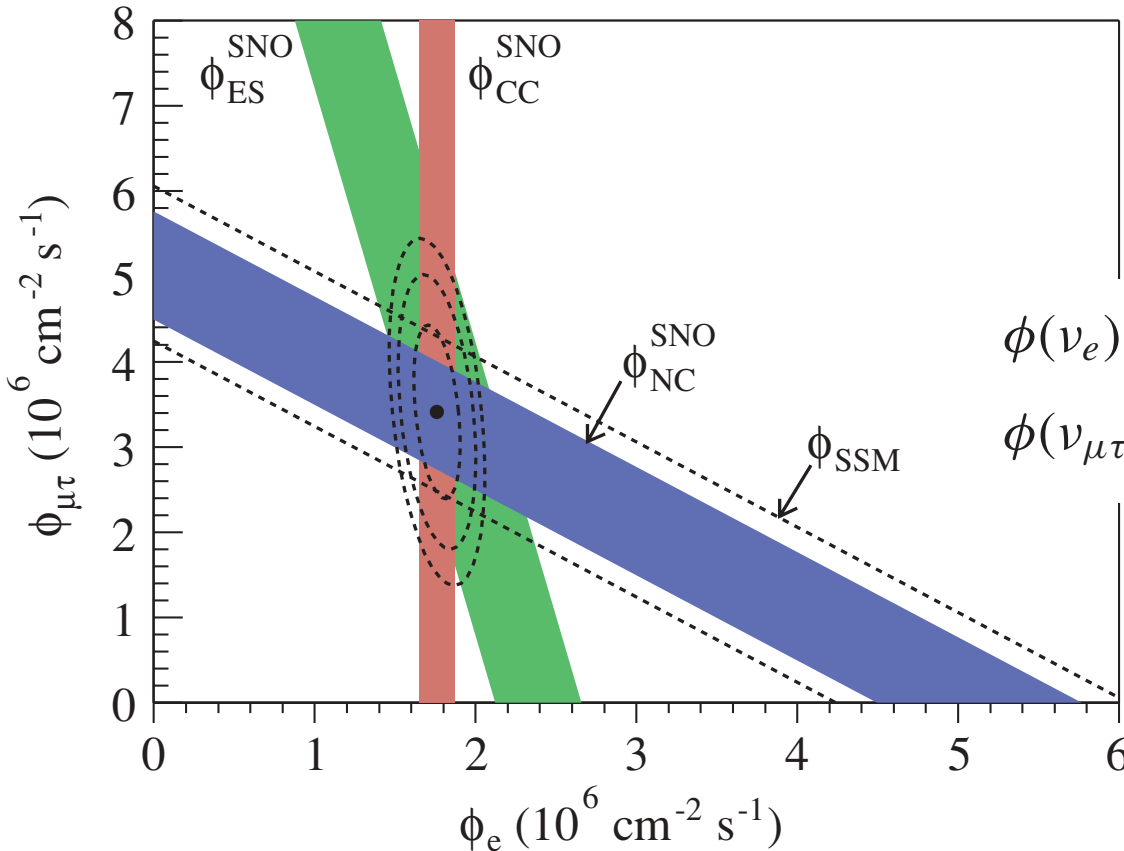
reconstructed neutrino direction w.r.t. sun

# The SNO experiment

$$\phi_{CC} = 1.76_{-0.05}^{+0.06} \text{ (stat.)}_{-0.09}^{+0.09} \text{ (syst.)} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\phi_{ES} = 2.39_{-0.23}^{+0.24} \text{ (stat.)}_{-0.12}^{+0.12} \text{ (syst.)} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

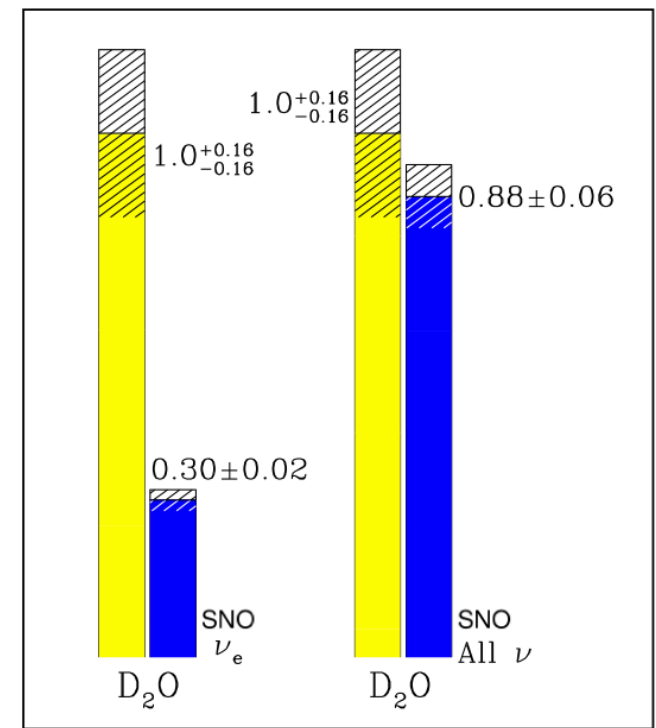
$$\phi_{NC} = 5.09_{-0.43}^{+0.44} \text{ (stat.)}_{-0.43}^{+0.46} \text{ (syst.)} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$



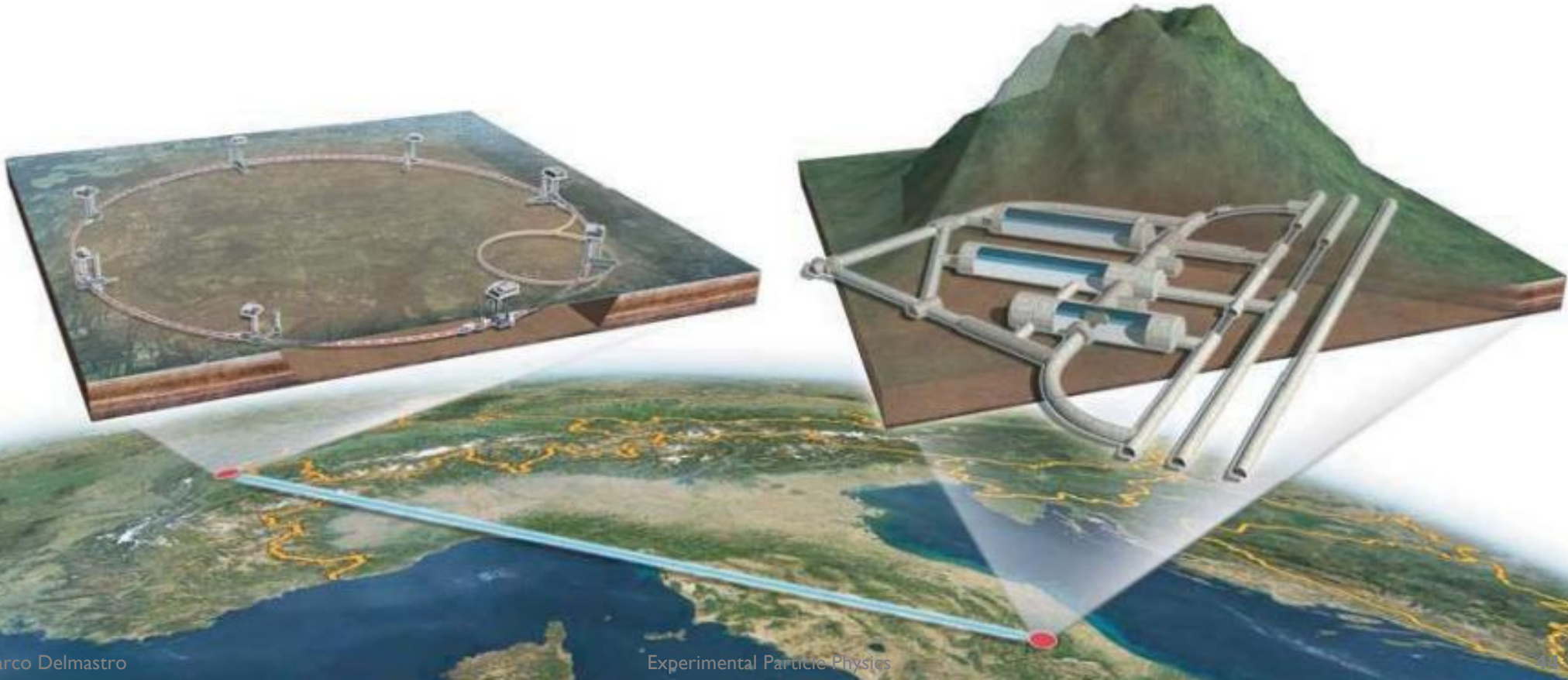
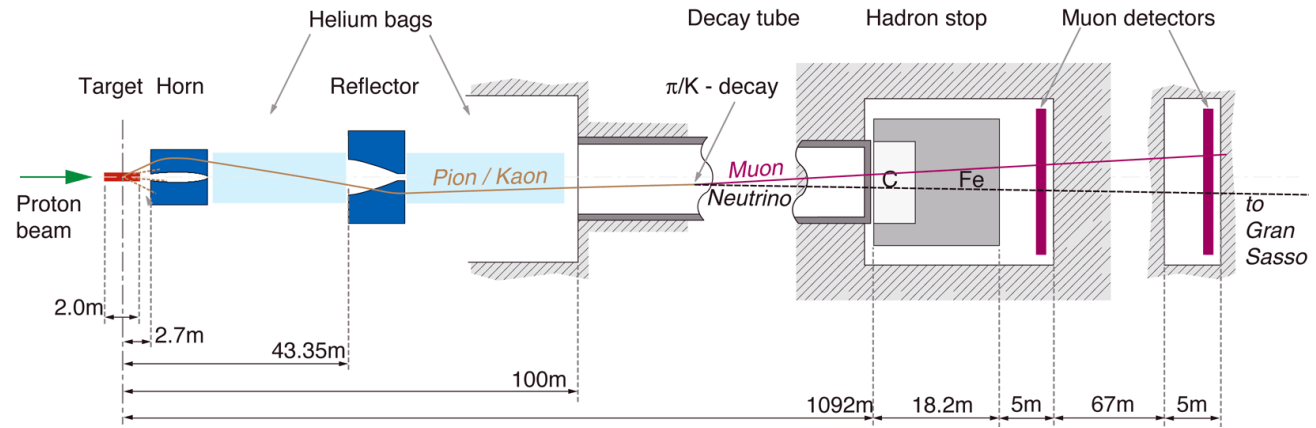
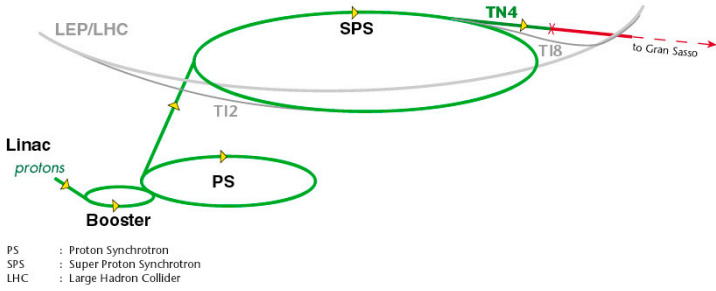
$$\phi(\nu_e) = 1.76_{-0.05}^{+0.05} \text{ (stat.)}_{-0.09}^{+0.09} \text{ (syst.)}$$

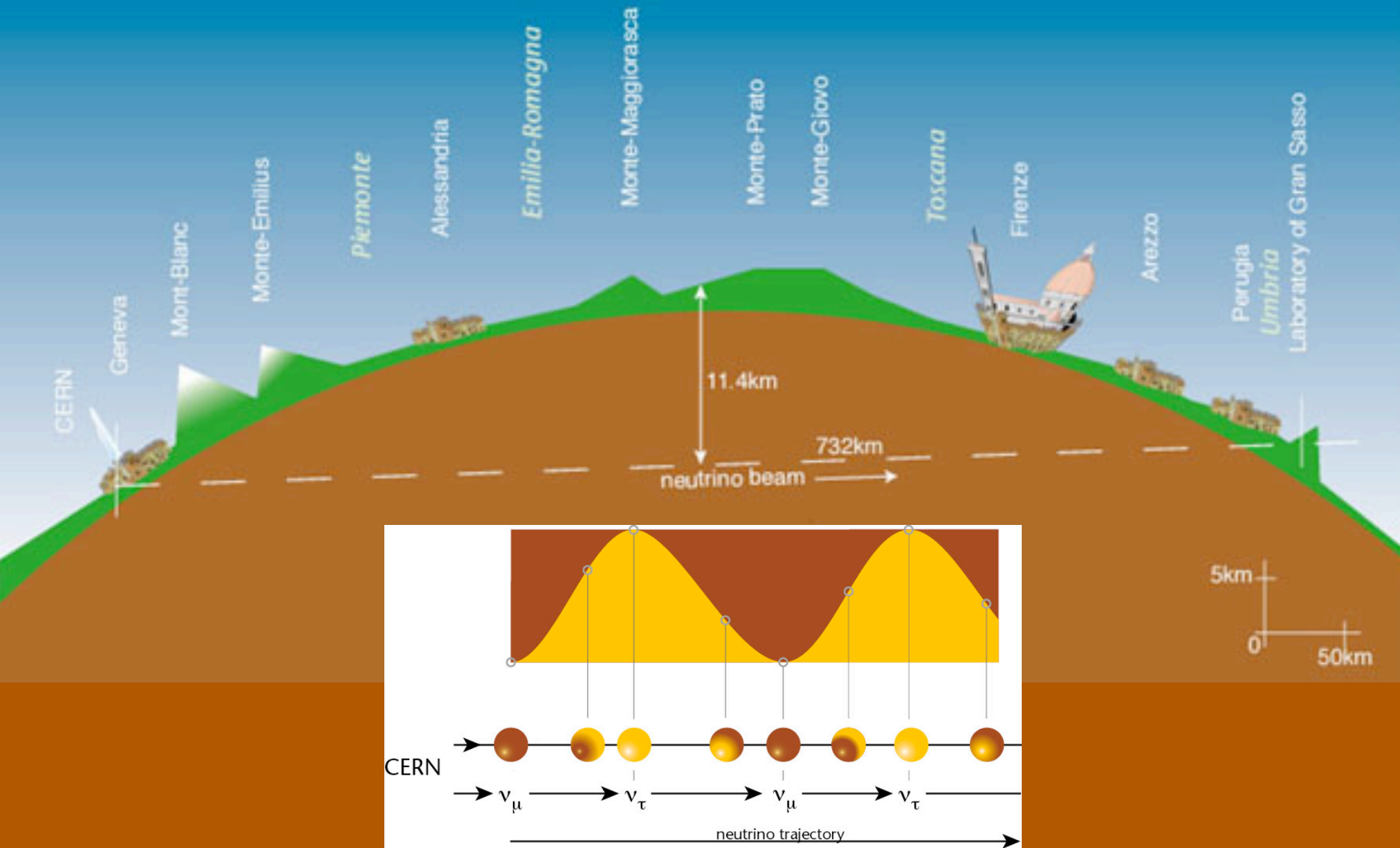
$$\phi(\nu_{\mu\tau}) = 3.41_{-0.45}^{+0.45} \text{ (stat.)}_{-0.48}^{+0.48} \text{ (syst.)} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

**$\nu_e$ -flux too low!  
Oscillations!**

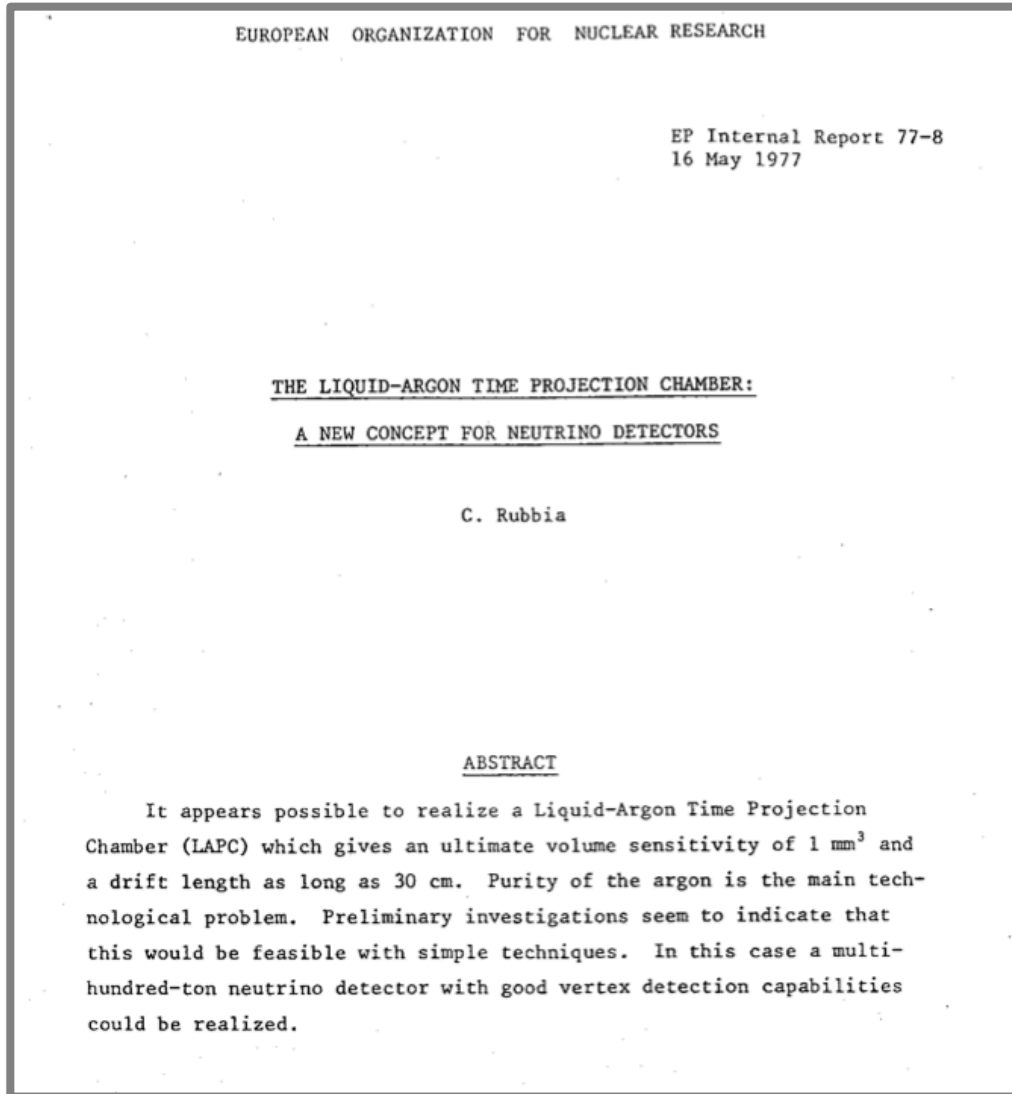


# CNGS





# TPC as neutrino detectors



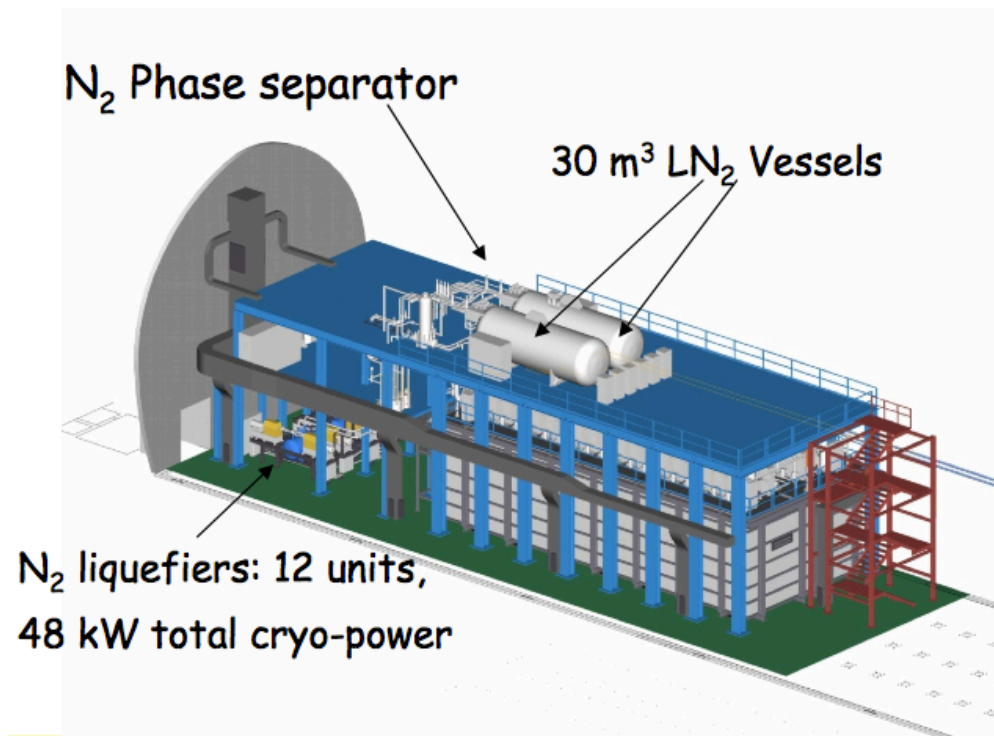
<http://cds.cern.ch/record/117852/files/CERN-EP-INT-77-8.pdf>

## Why LAr for neutrino detectors?

- Excellent insulator, very weakly electronegative: free electrons produced by ionization drift long distances
- Produces many electron-ion pairs: measurement of energy deposited in liquid;
- Good scintillator: measurement of energy of luminous flash produced by event, event localization
- Available in sufficient quantity

	Argon	CF <sub>3</sub> Br
Nuclear collision length	53.2	49.5 cm
Absorption length	80.9	73.5 cm
dE/dx, minimum	2.11	2.3 MeV/cm
Radiation length	14	11 cm
Density	1.40	1.50 g/cm <sup>3</sup>

# ICARUS (Imaging Cosmic And Rare Underground Signals)



Hall B @ LNGS



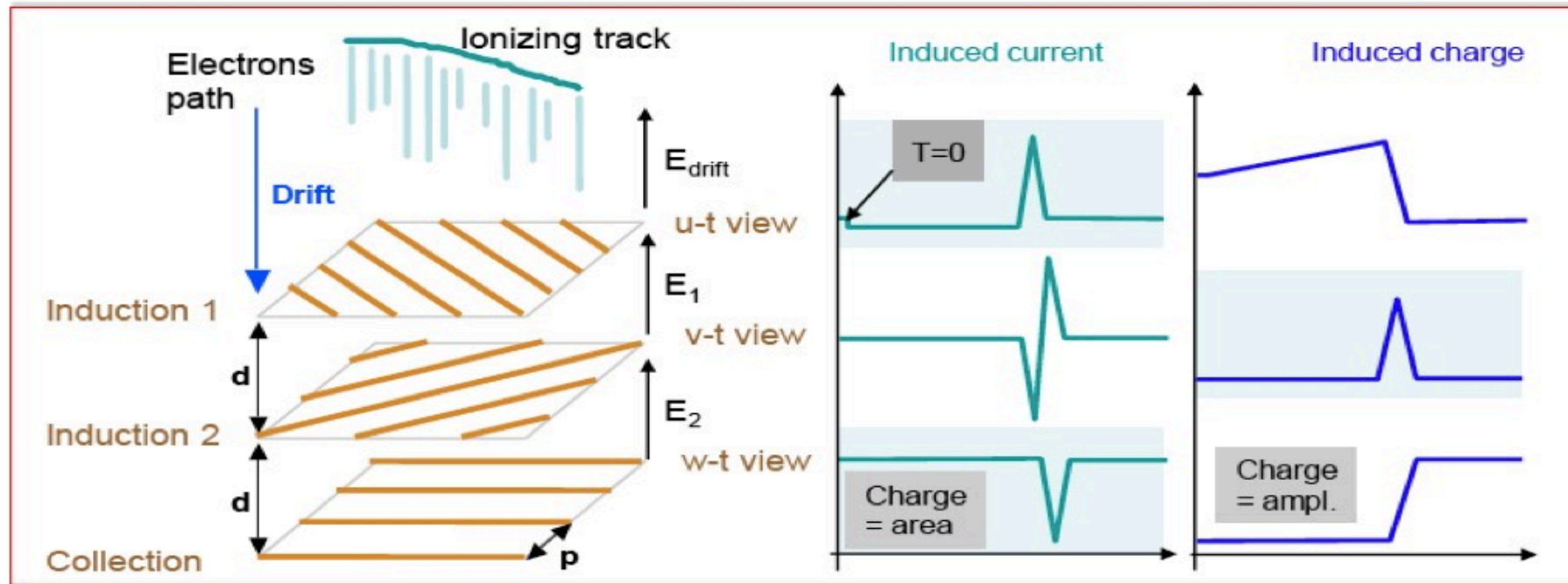
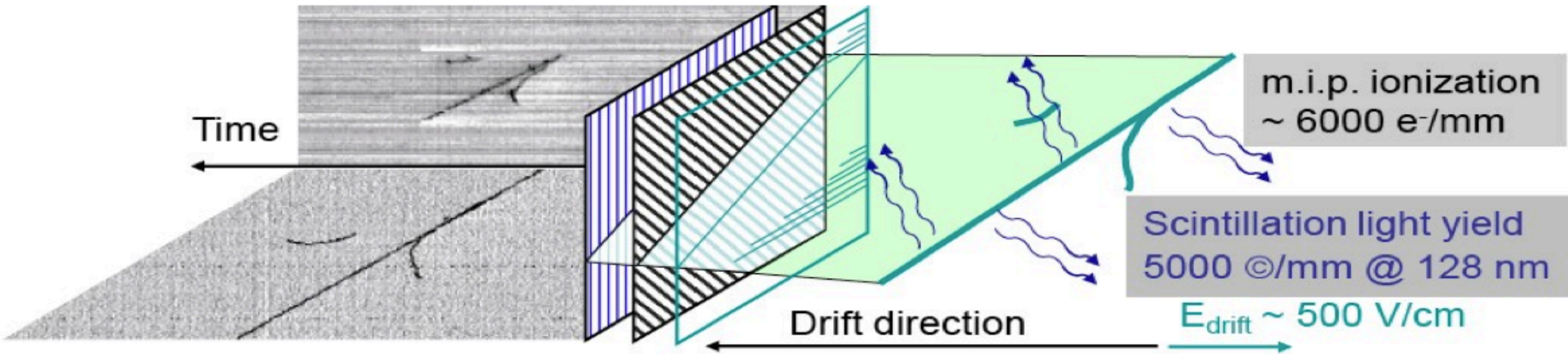
## ■ Two identical modules

- 3.6 x 3.9 x 19.6 ≈ 275 m<sup>3</sup> each
- Liquid Ar active mass: ≈ 476 t
- Drift length = 1.5 m (1 ms)
- HV = -75 kV E = 0.5 kV/cm
- v-drift = 1.55 mm/μs

## ■ 4 wire chambers:

- 2 chambers per module
- 3 readout wire planes per chamber, wires at 0,±60°
- ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light detection:
  - VUV sensitive (128nm) with wave shifter (TPB)

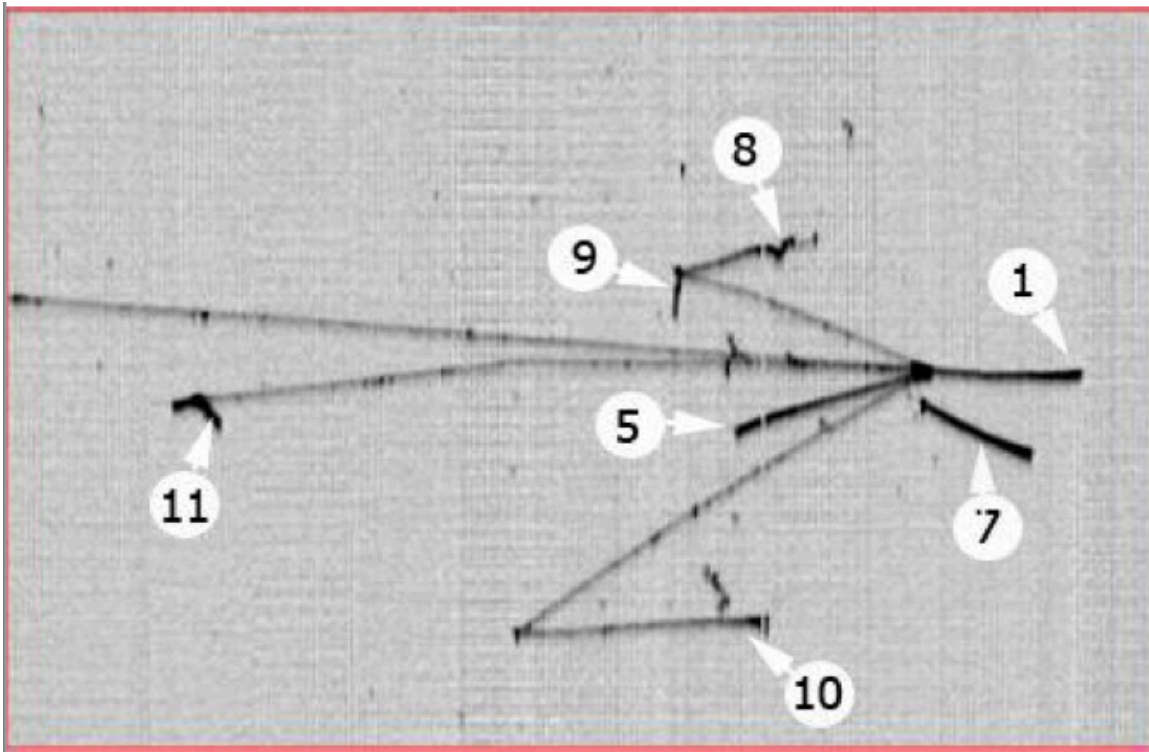
# ICARUS





# ICARUS

Run 9809 Event 651



6 protons and 1 pion which decays at rest  
muon:  $7.1 \pm 1.3$  [GeV/c]

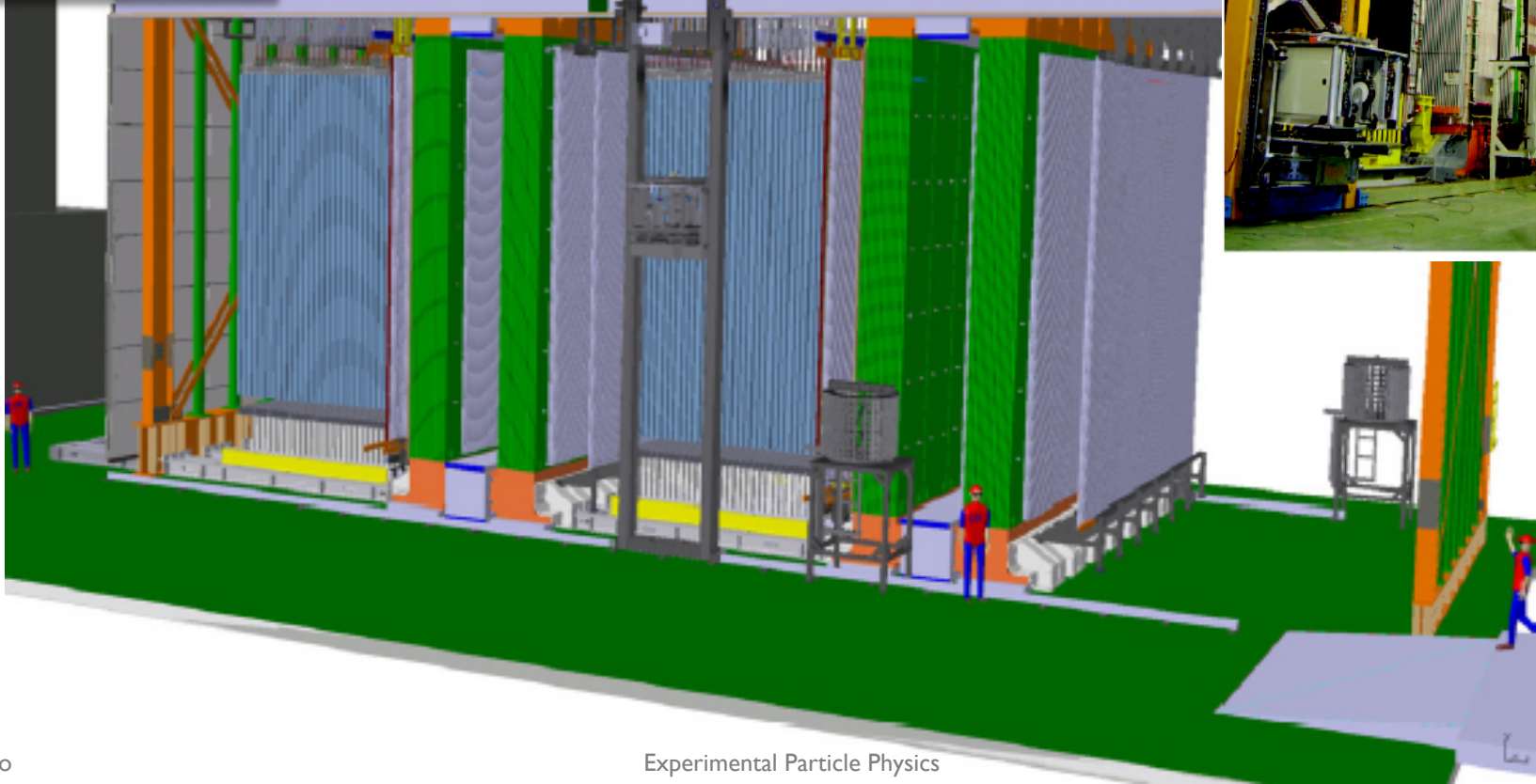
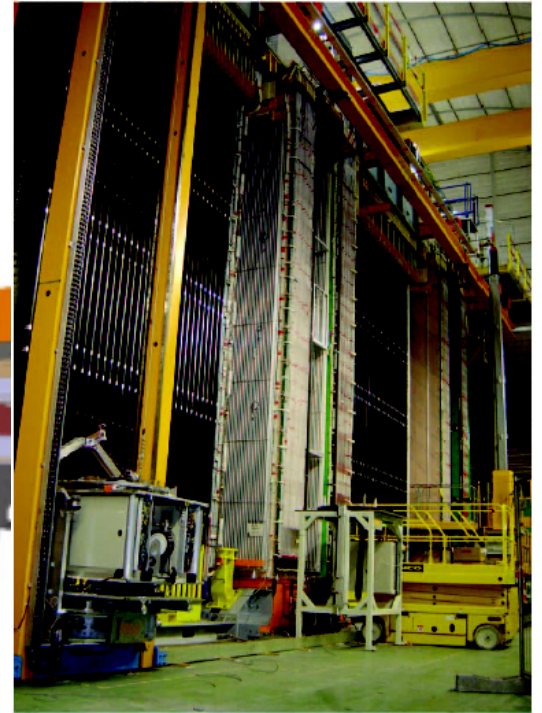
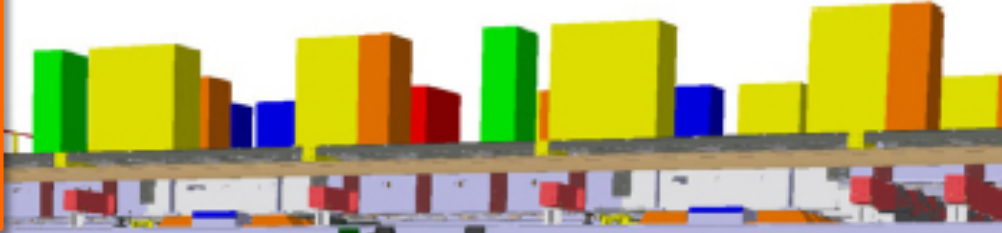
<http://icarus.lngs.infn.it/photos/NeutrinoEventsGallery/>

Particle identification based on  $dE/dx$  dependence:

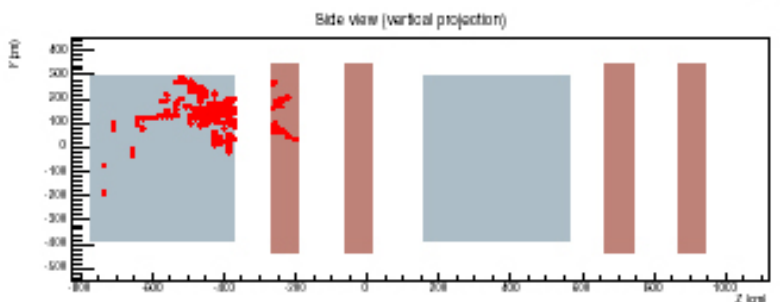
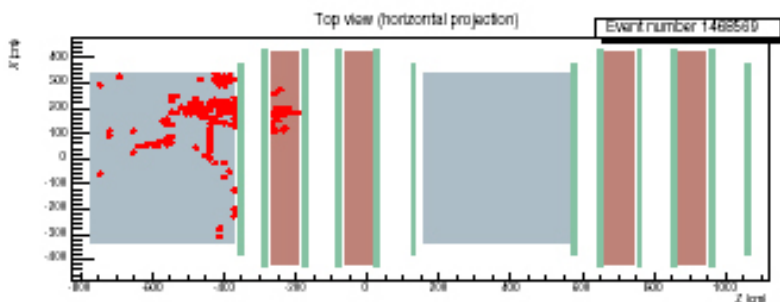
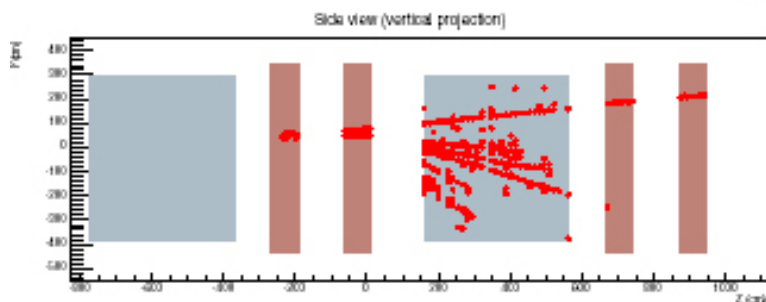
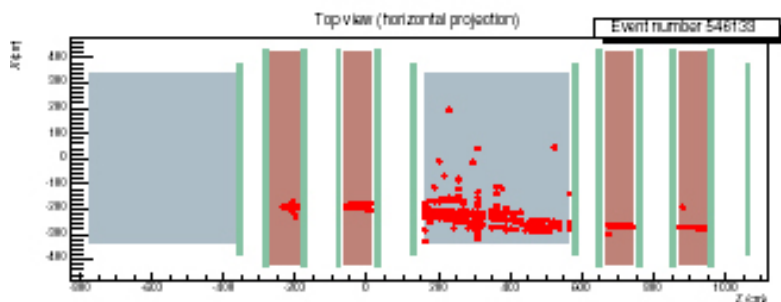
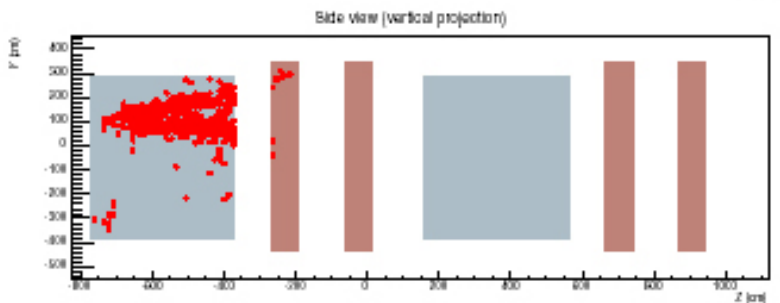
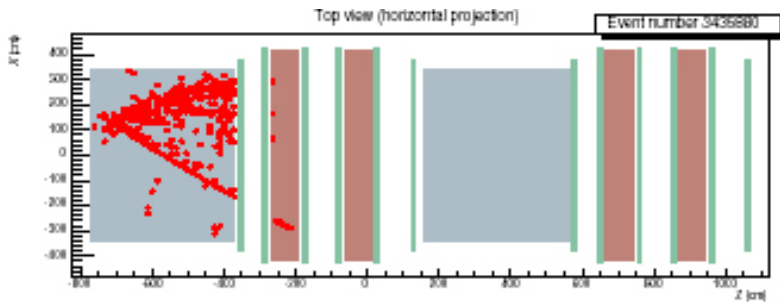
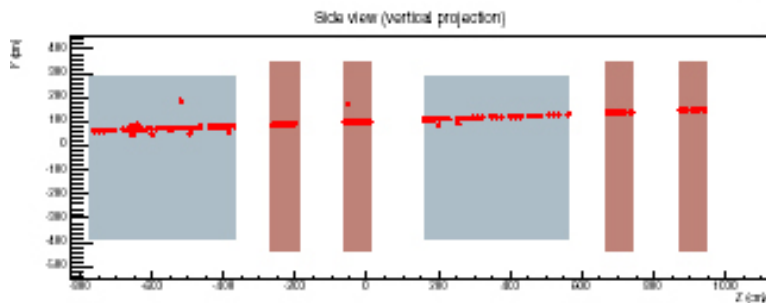
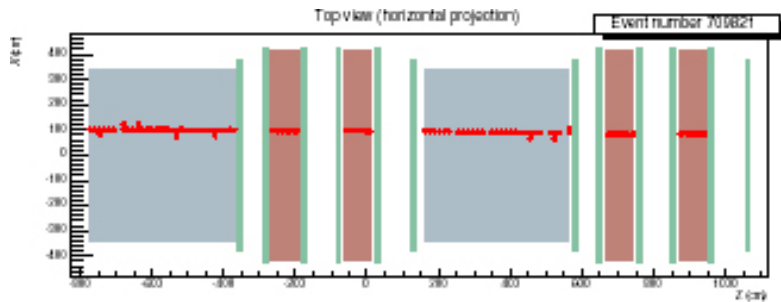
- Reconst. 3D track segments:  $dx$
- charge dep. on track segment:  $dE$

Track	$E_{\text{dep}}$ [MeV]	range [cm]
1(p)	$185 \pm 16$	15
5(p)	$192 \pm 16$	20
7(p)	$142 \pm 12$	17
8( $\pi$ )	$94 \pm 8$	12
9(p)	$26 \pm 2$	4
10(p)	$141 \pm 12$	23
11(p)	$123 \pm 10$	6

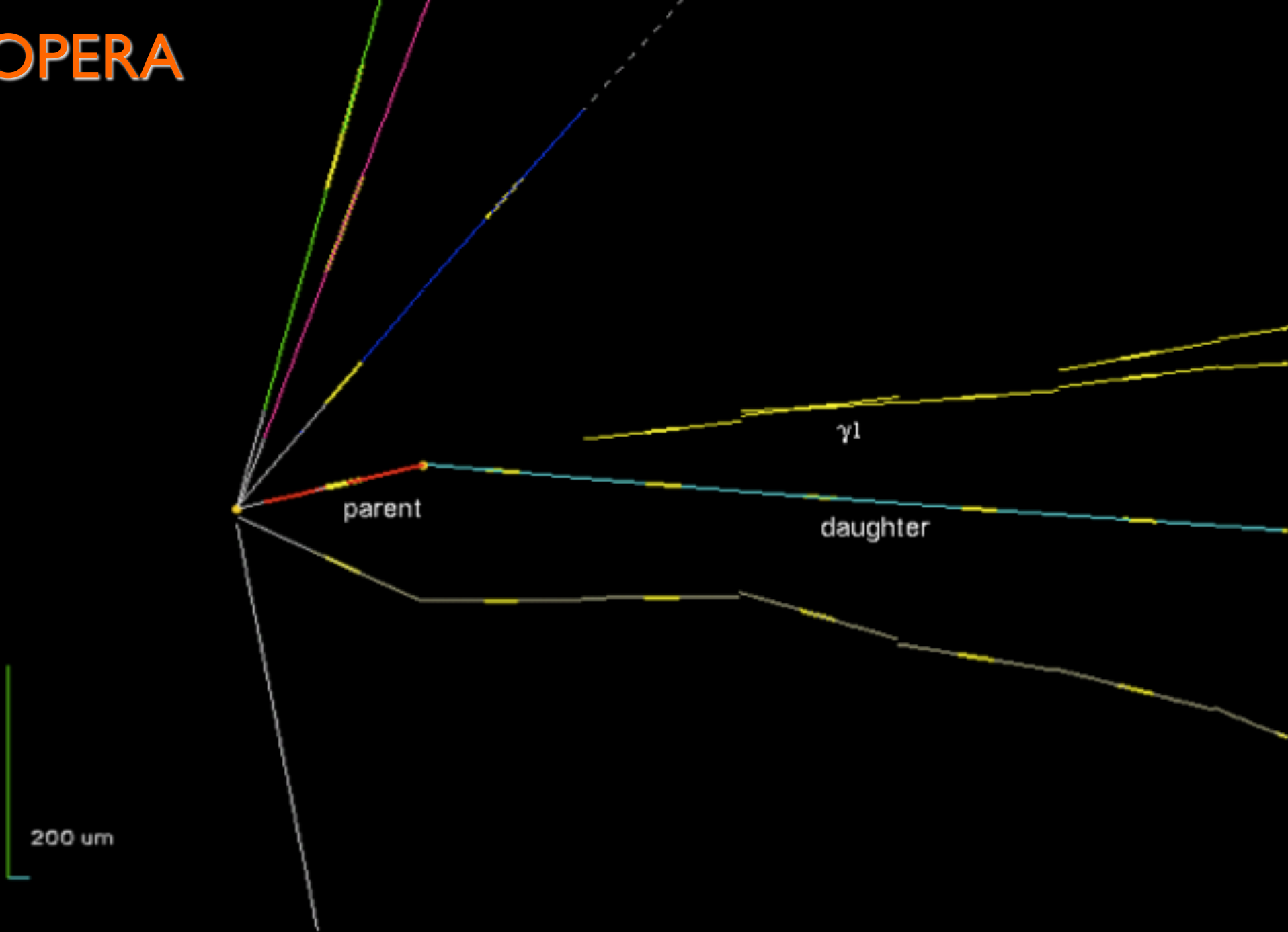
# OPERA (Oscillation Project with Emulsion-tRacking Apparatus)



# OPERA



# OPERA



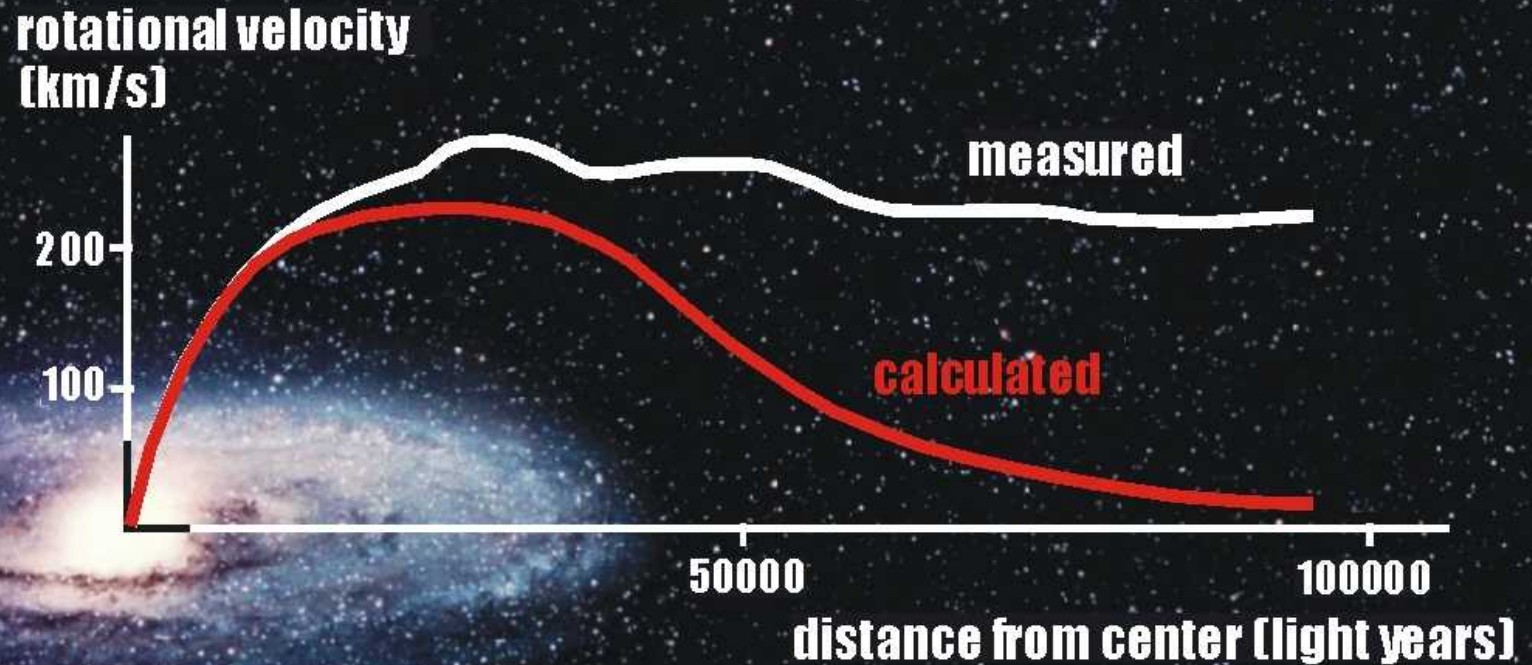


**300 000**  
**K<sub>M</sub>/S**



**LUMIÈRE**

# Dark matter astronomical evidence



# WIMP detection: cryogenic experiments

WIMPs = Weakly interacting massive particles ...

Dark matter particles; must be neutral, i.e. must neither interact via electromagnetic nor strong interactions; WIMPs must be heavy, i.e. non-relativistic (cold dark matter) in order to allow for galaxy formation ...

Assumed mass range: 10 GeV - 10 TeV

Mass limits dependent on cross section ...

[e.g.:  $\sigma_{\chi p} = 1.6 \cdot 10^{-7}$  pb yields  $m_{\text{WIMP}} > 60$  GeV]

## Detection via elastic $\chi p$ -scattering ...

Assume WIMP velocity:  $v_\chi \approx 300$  km/s, i.e.  $\beta = 10^{-3}$  ...

Solar system speed w.r.t. to milky way:  $v = 250$  km/s

Velocity of earth moving w.r.t solar system:  $v = 30$  km/s

Maximum energy transfer:

$$T_K^{\text{max}} = 2 \frac{m_\chi^2 M_K c^2}{(m_\chi + M_K)^2} \beta^2 \approx 2M_K v_\chi^2 \quad \left[ \begin{array}{l} m_\chi \gg M_K \\ M_K = 100 \text{ GeV} \\ \rightarrow T_K^{\text{max}} \approx 100 \text{ keV} \end{array} \right]$$

# How to detect WIMP?

Transferred energy of recoiling nuclei generally much smaller ( $< 10\%$ ) ...  
Need detector that allows nuclei detection below keV range ...

Energy resolution requires:  $N_{\text{excite}} \gg 1$   
i.e.  $E_{\text{excite}} \ll 1 \text{ eV}$

Remember:        Gases    –    ionization energy  $\approx 30 \text{ eV}$   
                     Silicon    –    electron/hole pair creation  $\approx 3 \text{ eV}$

Better possibilities:

Phonon excitation:

Maximum phonon energy in Si is 60 meV; roughly 2/3 of the energy required for electron-hole formation goes into phonon excitation ...

Superconducting detectors:

In superconductors the energy gap  $2\Delta$  is equivalent to the band gap in semiconductors; absorption of energy  $> 2\Delta$  (typically 1 meV) can break up a Cooper pair ...

Cryogenic detectors:

Detect low energies  
with very good resolution ...



# Cryogenic detectors

## Phonon Detectors ...

Assume thermal equilibrium:

Convert absorbed energy  
into phonons:

$$\Delta T = E/C$$

C: heat capacity of the sample  
[specific heat × mass]

E: deposited energy

Optimal detector: low heat capacity

Example 1: Si-detector at room temperature ...

$$C_{\text{spec}} = 0.7 \text{ J/gK}; E = 1 \text{ keV}; m = 1 \text{ g} \rightarrow \Delta T = 2 \cdot 10^{-16} \text{ K}$$

Not very practical ...

Need lower specific heat and mass ...

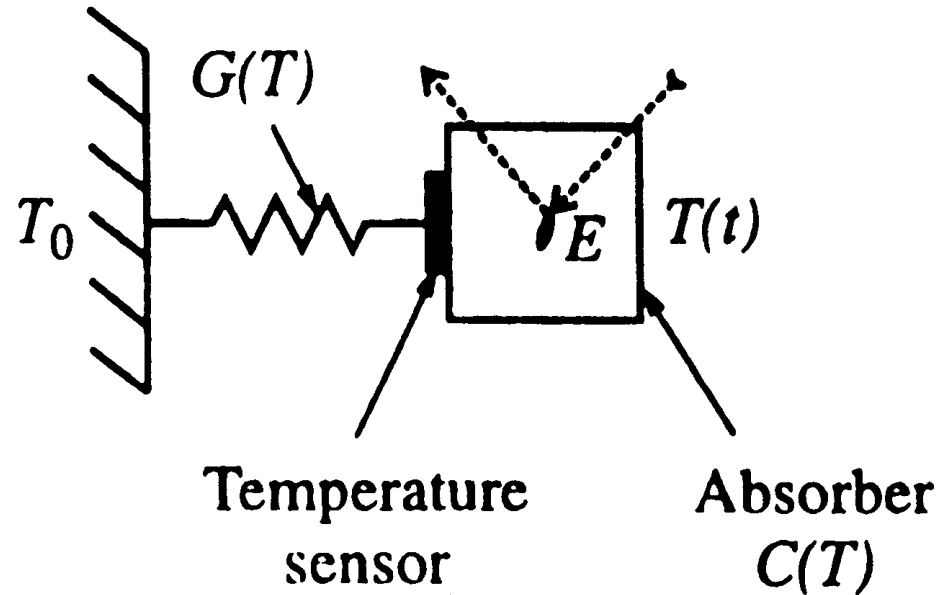
Example 2: Si-detector at low temperature ...

$$C_{\text{spec}} \propto (T/\Theta)^3; C_{\text{spec}} = 2 \cdot 10^{-15} \text{ K}; T = 0.1 \text{ K};$$

$$E = 1 \text{ keV}; m = 15 \mu\text{g}$$

$$\rightarrow \Delta T = 0.04 \text{ K [possible!]}$$

Basic configuration  
of cryogenic calorimeter



Resolution:

$$n = CT/kT = C/k$$

$$\sigma_0 = kT\sqrt{n} = \sqrt{(CKT^2)}$$

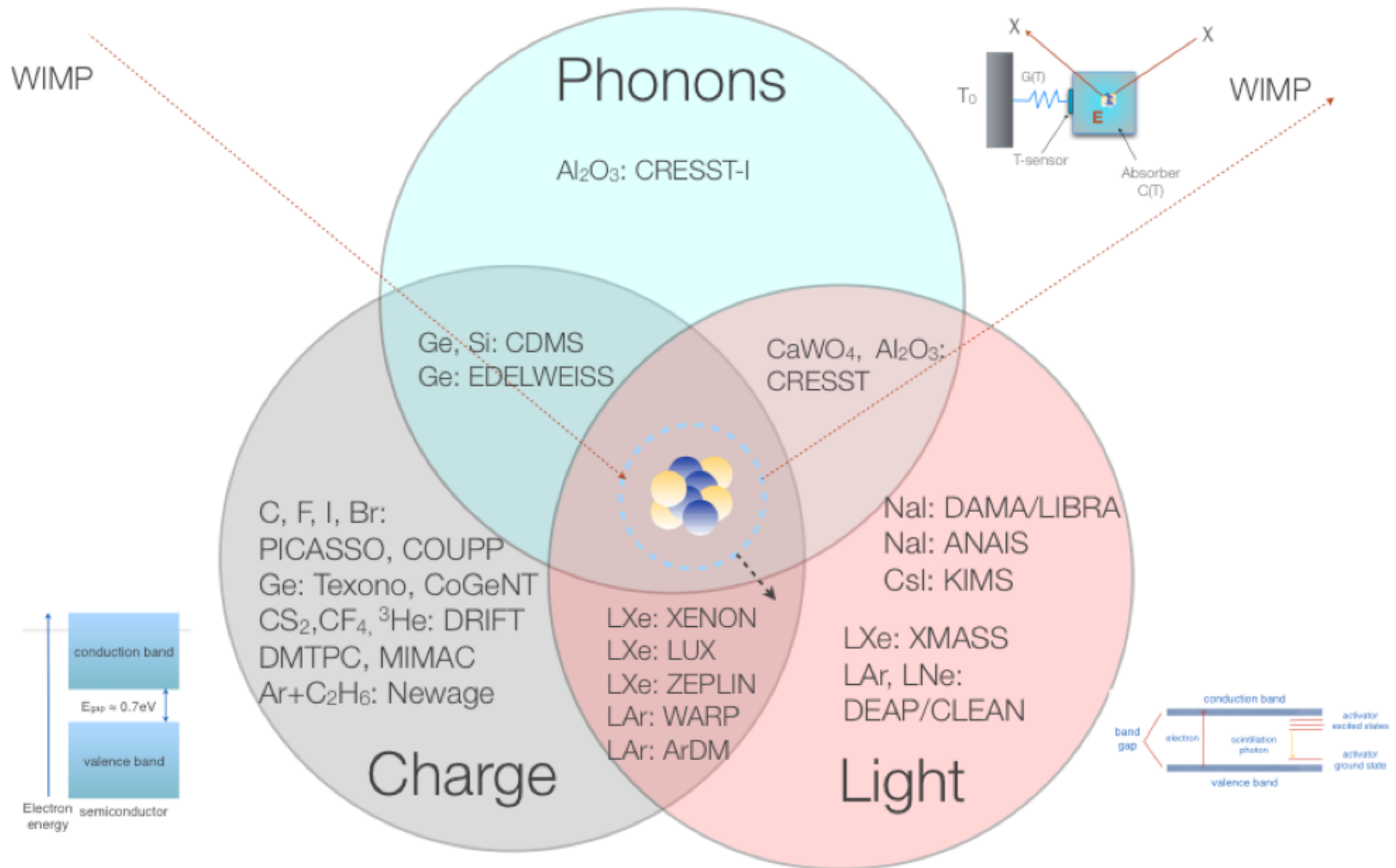
$$\sigma_E = \epsilon_{\text{Ph}}\sqrt{(E/\epsilon_{\text{Ph}})} = \sqrt{(kTE)}$$

$$\sigma = \sigma_0 + \sigma_E$$

Yields:  $\sigma < 0.2 \text{ eV}$

[Si Semiconductor detector:  $\sigma = 20 \text{ eV}$ ]

# Dark matter detection overview



# Dark matter detection

## Example: CDMS

[Soudan Underground Lab]

5 towers each with 6 Ge/Si detectors  
operated at  $T \approx 20$  mK ...

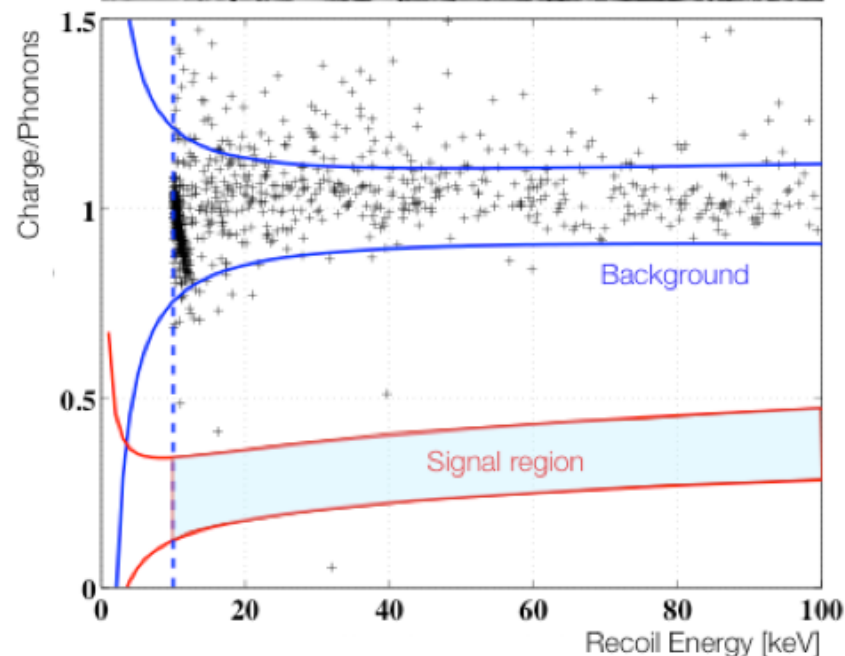
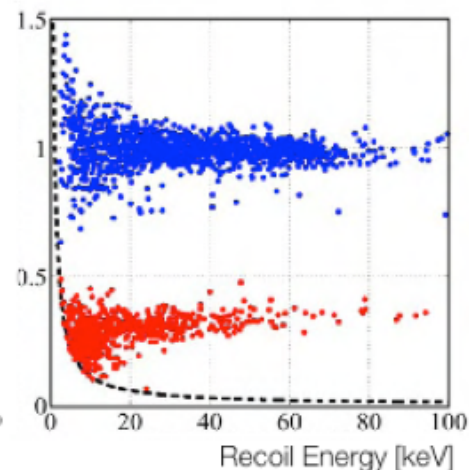
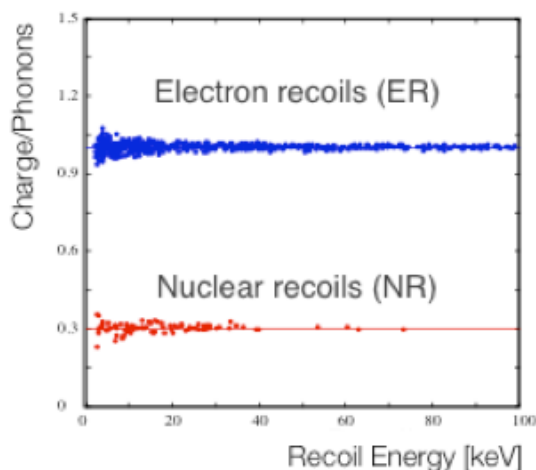
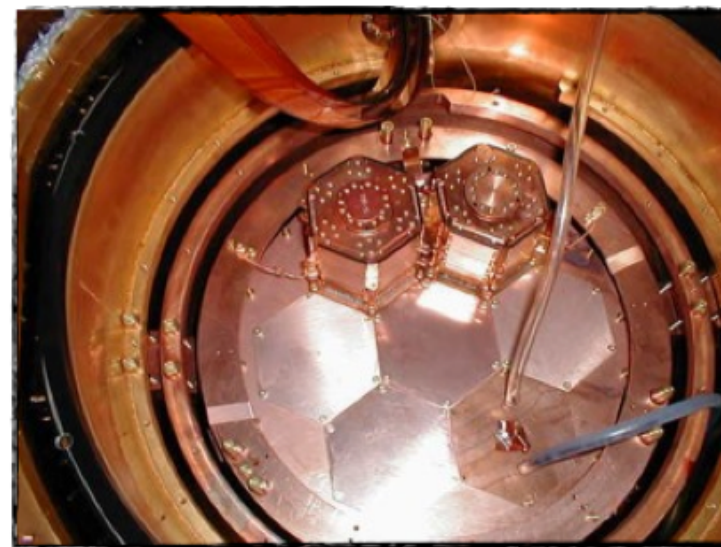
Double readout:

- Temperature change (Phonons)
- Charge readout (Ionization)

Idea:

- WIMPs (and neutrons) scatter off nuclei
- Most background noise sources ( $\gamma, e$ ) scatter off electrons
- Different response to nuclear recoils than to electron recoils

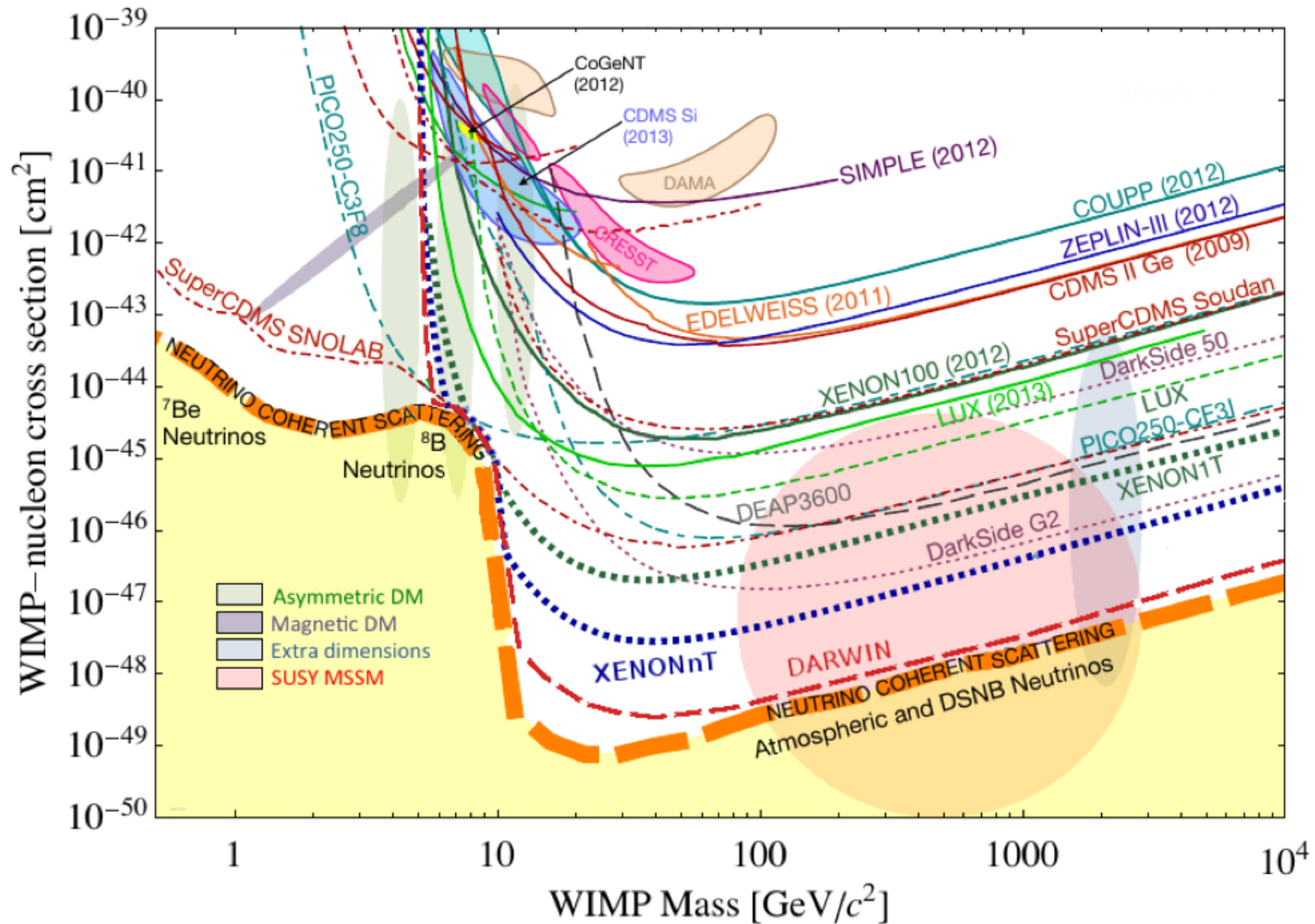
View into  
CDMS Experiment



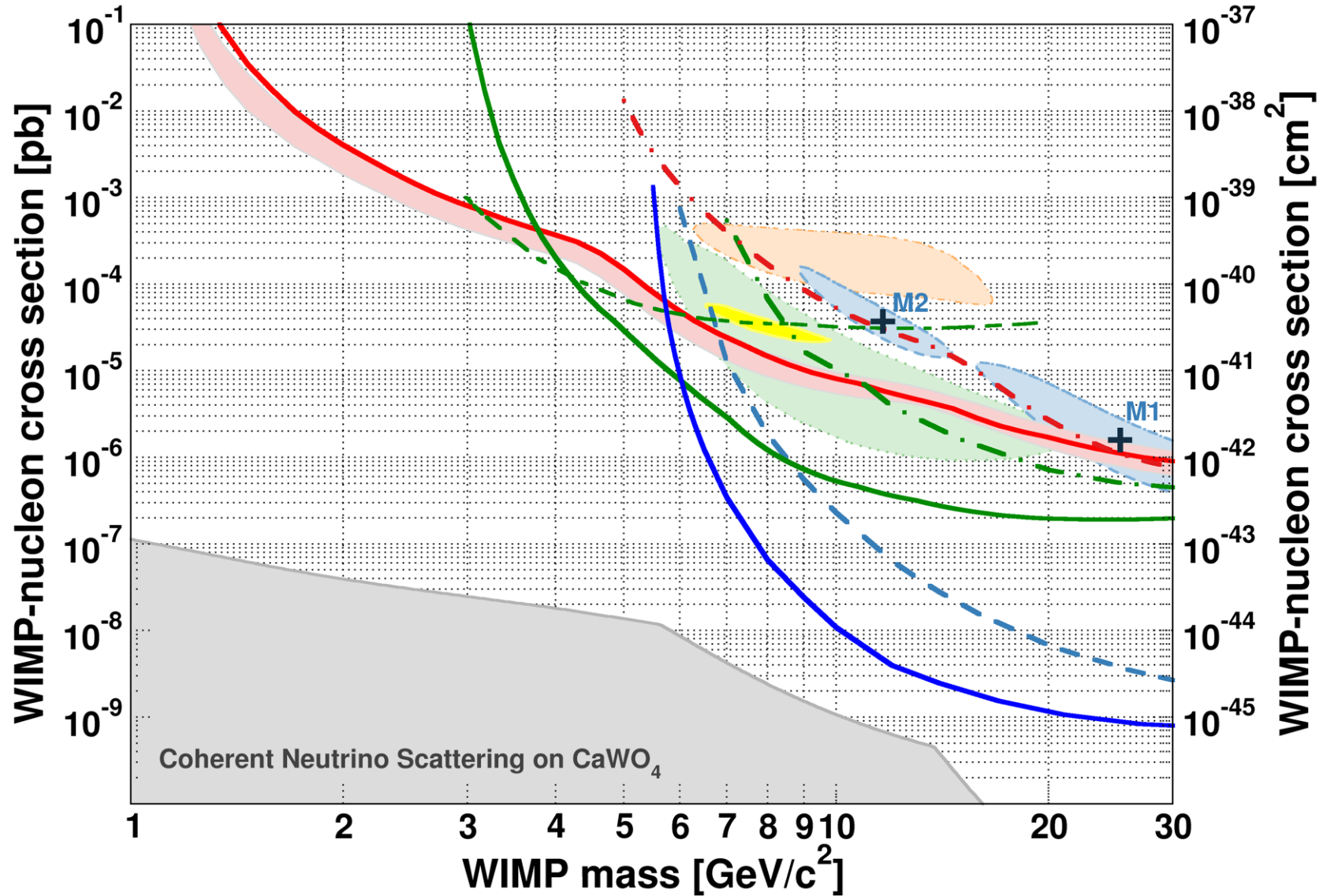
# Did anyone observe signs of dark matter?

- By 2015 3 experiments claim evidence for potential DM signals
  - ✓ DAMA/LIBRA (Gran Sasso)
    - $9.3\sigma$  for annual modulation of single-hit events
      - 2-6 keV energy,  $(0.0112 \pm 0.0012)$  counts/kg/keV/day amplitude;  $(144 \pm 7)$  days phase;  $(0.998 \pm 0.002)$  years period
  - ✓ CoGeNT (Soudan Underground Lab)
    - $\sim 2\sigma$  DM excess, annual modulation
  - ✓ CDMS-II (SNOLAB)
    - 3 unexplained low-energy events in Si-detector sample
  - ✓ After detector upgrade, CRESST-II no longer finds previously claimed excess
- All claimed excesses cluster in mass region of tens of GeV with cross sections between  $10^{-42}$  and  $10^{-39}$  cm<sup>2</sup>
- All other direct detection searches have set **exclusion limits** on the dark matter-nucleus cross section that **contradict the claims** listed above

# Did anyone observe signs of dark matter?



# Did anyone observe signs of dark matter?



Finding new particles that constitute dark matter would be a major breakthrough in physics. As extraordinary new findings require extraordinary evidence, the hurdles are high. Various unusual experimental results of the last decade have been interpreted in terms of dark matter, but all of them could also be the result of a misunderstood background or other effects.

M. Klasen, M. Pohl, G. Sigl

***Indirect and direct search for dark matter***

<https://arxiv.org/abs/1507.03800>